INTERNATIONAL TOWING TANK CONFERENCE

Dictionary of Hydromechanics

Prepared by the Quality Systems Group of the 30th ITTC

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INTRODUCTION

This Dictionary is intended for a broad readership including practising naval architects who wish to acquire and apply knowledge of hydrodynamics and also physicists and theoretical hydrodynamicists who wish to apply their particular knowledge to the solution of ship problems.

Engineering, physical and nautical terms in common use have not been included when did not require special definition in the context of ship hydrodynamics or when their meanings were self-evident. The work is arranged in the following sections prefaced with a brief reference to the nature if their content:

1. General
2. Ship Geometry
3. Resistance
4. Propeller (including propeller geometry)
5. Cavitation
6. Seakeeping
7. Manoeuvrability
8. Performance (in the context of speed and power)
9. Offshore Engineering
10. Computational Fluid Dynamics

The order of entry for each item is: title, symbol, dimensions, followed by the definition. In each section the titles are arranged in alphabetical order. In this way, having found the item required, perusal of the section will indicate other related items which may be of interest. For general reference, there is an overall alphabetical index of all titles and against each is given the section and page where the item is to be found.

The symbols given are in accordance with those in the latest ITTC symbols list which is a complementary document. In a number of instances, the list gives alternative symbols and these are generally included except where a definite preference is indicated.

Items needing clarification are those in red fonts.

1. GENERAL

1. Definition of general terms of wide application

Under this heading is listed a number of general terms frequently encountered in the field of naval architecture and marine engineering. To ensure that their general meanings are retained and that they are employed in the proper manner, their definitions are given here.

Axes co-ordinate— Generally, a system of rectangular Cartesian co-ordinates and in particular:

Body axes (x, y, z) —A right hand orthogonal system fixed in the body or ship. In general, the x axis is directed forward, y axis to port and z axis upward. **NOTE: This definition deviates from the ISO Definition.** The x axis is forward and parallel to the reference or baseline used to define the body's shape. For dynamic considerations the origin should be at the centre of the gravity of the body and the z axis vertically downwards. The y axis is to starboard.

Fixed axes (x_0, y_0, z_0) — A right hand orthogonal system nominally fixed in relation to the earth; the positive z_0 axis is vertically downwards and the x_0 axis lies in the direction of initial motion.

Control— As a noun, is applied to the act of controlling or directing, such as when controlling the movements of body or directing a ship in the steering, turning, and diving manoeuvres.

Control surface— The rudders, hydroplanes, and other hinged or movable device used for controlling the motions of body or ship.

Controllability— That quality of a body or ship which determines the effectiveness of movement of the controls in the producing any desire change, at a specified rate in the attitude or position of the moving body or ship.

Controls —The means or system provided to enable the crew of a ship to control its speed, power, attitude, direction of motion, and the like.

Dynamic— As an adjective, pertains to motion as the result of force, or to bodies and system in motions; in this respect it is opposite of *static* (which see)

Dynamic stability— That property of body which cause it, when slightly disturbed from a steady motion, to resume that the same steady motion, usually along a different path, without any corrective control being applied.

Equilibrium— A state of balance, between opposing forces or actions.

Equilibrium conditions:

Static equilibrium conditions**:** — situations with no unbalanced forces and no accelerations.

Quasi-static equilibrium conditions: —situations with only slightly unbalanced forces and low accelerations. Use of static equilibrium analysis techniques is an acceptable substitute in these conditions.

Near-equilibrium dynamic conditions*:* —situations where using average or periodic unbalanced forces and assuming average or periodic accelerations is the only way to analytically solve otherwise complicated problems. This includes dynamic situations which can be assumed to be periodic or a stationary random process so that Fourier Transform methods are valid in the frequency domain.

Far-from-equilibrium dynamic conditions**:** —significant unbalanced forces and complex accelerations make time domain analysis of the pressure and velocity field equations of fluid mechanics non-computable without extremely high computational times. This includes all situations in which a non-stationary random process is present. (Note that Newton's Second Law for rigid bodies does not have these restrictions so body centric analysis is computable.)

Inertial instability—generally, instability in which the only form of energy transferred between the steady state and the disturbance in the fluid is kinetic energy. *(McGraw Hill Dictionary of Scientific and Technical Terms*

Specific— As an adjective, often applies in English-speaking countries to the ratio between some quantity to be defined and a standard quantity having the same characteristics, which is take as a reference. The best known term of this kind is the expression “specific gravity”. Here the specific gravity is the dimensionless ratio of weight of unit volume of the designated substance to the weight of unit volume of fresh water. In other countries the term “specific” generally refer to absolute values per unit volume and is not expressed in terms of properties of a reference substance, such as water.

Stability— The property, quality, or characteristic of a body, which cause it, when its equilibrium is disturbed, to develop forces or moments acting to restore its original condition.

Static— As an adjective, pertains to bodies or system at rest or forces in equilibrium; in this respect it is the opposite of *dynamic* (which see)

Steady state— This applies to a condition may be static, but is generally dynamic, in which there is no change with time. A ship moving in a straight line at uniform speed and a ship in a steady turn at uniform speed both represent steady state conditions.

Unsteady or transient— These apply to a condition which is invariably dynamic, in which the motion of body or the flow of a liquid changes with time, with reference to an assumed set of axes.

2. Mathematical Foundations

1.1.1 Deterministic Analysis

Deterministic System: — is a system in which no randomness is involved in the development of future states of the system. Linear deterministic models thus produce the same output for a given starting condition. Non-linear deterministic models can produce multiple outputs. See also **chaotic** sys**tems.**

1.1.1.1 System Dynamics

Attractors — See also Conservative and dissipative systems.

Flow: —As an example, (See Figure1-1) shows the flow of a damped pendulum. The black arrows of the vector field **F** are tangential at the trajectories. In a two-dimensional phase space, you can draw a qualitative picture of the flow and the orbits. First, draw the so-called null clines. These are the lines were the time derivative of one component of the state variable is zero. Here, one null cline is the angle axes because the time derivative of the angle is zero when the angular velocity is zero. The other null cline is $\omega = -\omega_0^2 \sin\omega\varphi/\gamma$. On these null clines, draw the vector field vertical or horizontal, respectively. Between the null clines draw the vector field in the direction north east, south east, south west, or north west. The direction is determined by the signs of $d\varphi/dt$ and $d\omega/dt$. At the crossing points of the null clines, the vector field is zero, i.e., $d\varphi/dt = 0$ and $d\omega/dt = 0$. These points are called **fixed points**. They correspond to stationary solutions. Fixed points are examples of non-wandering sets. They can be either stable or unstable.

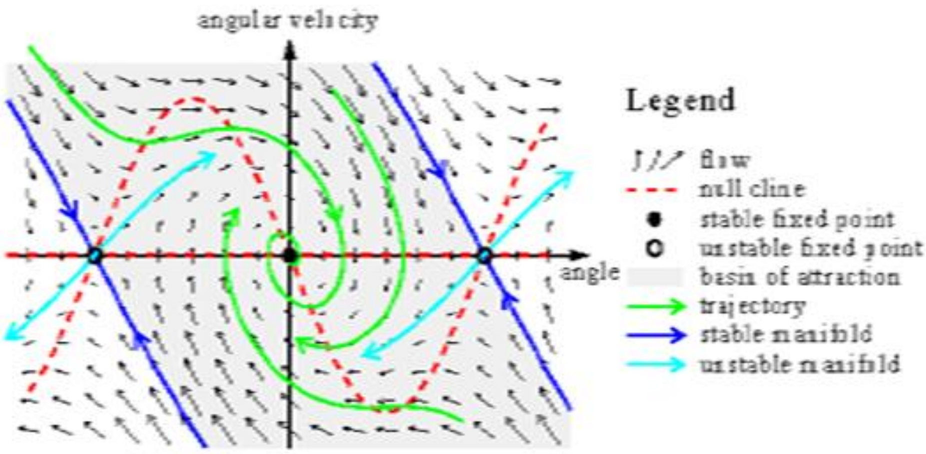


Figure 1-1 Flow.

Poincare Maps— A carefully chosen (curved) plane in the phase space that is crossed by almost all orbits. It is a tool developed by Henri Poincaré (1854-1912) for a visualization of the flow in a phase space of more than two dimensions. The Poincaré section has one dimension less than the phase space. The **Poincaré map** (See Figure 1.2) maps the points of the Poincaré section onto itself. It relates two consecutive intersection points. Note, that only those intersection points counts which come from the same side of the plane. A Poincaré map turns a continuous dynamical system into a discrete one. If the Poincaré section is carefully chosen, no information is lost concerning the qualitative behavior of the dynamics. Poincaré maps are invertible maps because one gets $\boldsymbol{u}_{\mathrm{n}}$ from $\boldsymbol{u}_{n+1}$ by following the orbit backwards.

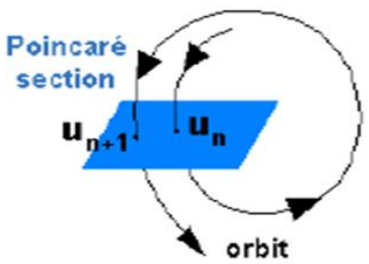


Figure 1-2 Poincare Map.

Chaotic orbits: — Bound non-periodic solutions. These solutions occur in driven pendula if the driving is strong enough. The first three types can also occur in linear dynamics. The fourth type appears only in nonlinear systems. Its possibility was first anticipated by the genius of Henri Poincaré (1854-1912). In the meanwhile, computers had turned this previously counter-intuitive behavior into a widespread experience. In the seventies, this irregular behavior was termed deterministic chaos. In the Poincaré map, limit cycles become fixed points. A non-wandering set can be either **stable** or **unstable**. Changing a parameter of the system can change the stability of a non-wandering set. This is accompanied by a change of the *number* of non-wandering sets due to a bifurcation.

Lorenz attractor, —named for Edward N. Lorenz, is a 3-dimensional structure corresponding to the long-term behavior of a chaotic flow, noted for its butterfly shape (Figure 1-3). The map shows how the state of a dynamical system (the three variables of a three-dimensional system) evolves over time in a complex, non-repeating pattern.
(http://en.wikipedia.org/wiki/Lorenz_attractor)

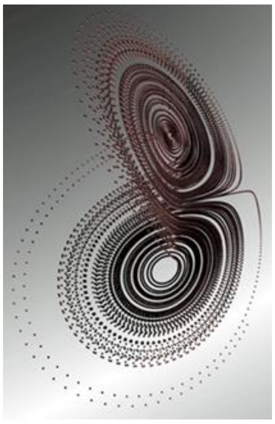


Figure 1-3 Lorenz attractor.

Boundedness — is that property of a solution to a differential equation to remained bounded that is remain within a certain prescribed non-infinite value or not diverge beyond a certain value.

Safe Basin — that region in the phase space or Poincare map where solutions remain bounded.

Chaotic system —-A deterministic but non-linear dynamical system which produces multiple outputs for a given set of initial conditions.

Conservative and Dissipative systems (Reference 4, page 108: Mainzer, 2007)—Since Poincaré's celestial mechanics (1892), it was mathematically known that some mechanical systems whose time evolution is governed by nonlinear Hamiltonian equations could display chaotic motion involving vortex points in the phase plane. Mathematically, nonlinearity is a necessary, but not sufficient condition of chaos. It is a necessary condition, because linear differential equations can be solved by well-known mathematical procedures (Fourier transformations) and do not lead to chaos. The system Lorenz used to model the dynamics of weather differs from Hamiltonian systems a la Poincaré mainly by its dissipativity (irreversible entropy generation and mathematical spiraling point attractors) Roughly speaking, a mathematical description of a dissipative system involving friction is not conservative but open with an external control parameter that can be tuned to critical values causing the transitions to chaos, i.e. a thermodynamically open system which is operating far from thermodynamic equilibrium in an environment with which it exchanges energy and matter

Constitutive Equation (See Figure 1-4***)*** —An equation relating the stress tensor in Cauchy's Field Equations of Motion to the deformation rate tensor for both Newtonian and non-Newtonian fluids. To eliminate the shear stress component leaving only normal stresses (pressure) in the Euler Equations of Motion, the fluid is assumed to in inviscid, making the solutions time reversible (isentropic). Assuming viscous flow makes the solution irreversible and entropy generating. The Navier Stokes equations assume the shear stresses are linearly related to the combination of deformation rate and turbulent Reynold's stresses.

Coupling—The influence of one mode of motion on another, for instance, coupling between heave and pitch.

Damping—A characteristic property of a dynamic system, which dissipates energy and the consequent reduction or decay of the motion.

Damping, viscous—A reduction in vessel motion caused by viscosity and/or flow separation resulting in energy dissipation.

Deterministic system— A system in which no randomness is involved in the development of future states of the system. Linear deterministic models thus produce the same output for a given starting condition. Non-linear deterministic models can produce multiple outputs. See also **chaotic** and

stochastic systems.

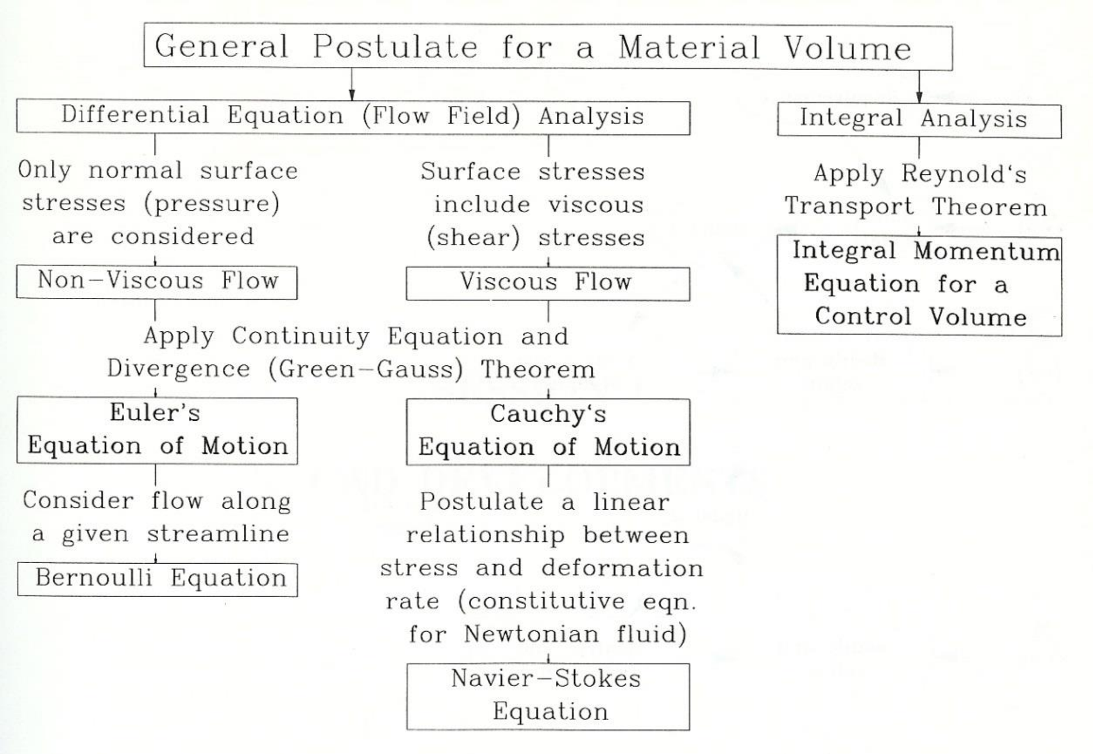


Figure 1-4 Development of Equations of Motion (See References 15 and 17, page 108).

Dynamical systems: —A part of the world which can be seen as a self-contained entity with some temporal behaviour. In nonlinear dynamics, speaking about a dynamical system usually means to speak about an abstract mathematical system which is a **model** for such an entity. Mathematically, a dynamical system is defined by its state and by its dynamics. A damped pendulum is an example of a dynamical system.

1. **Computability in complex dynamic systems:** — "The fundamental questions of complexity theory refer to the measurement of the speed, computational time, storage capacity and so on, of algorithms. It is another question how one sets out to find more or less complex algorithms." (Mainzer 2007, p 191)
2. "According to the 2nd law of thermodynamics, entropy is a measure of increasing disorder in isolated systems. The reversible process is extremely improbable. In information theory, entropy can be introduced as a measure of uncertainty of random variables" (Mainzer 2007, p 195)
3. **Predictions in chaotic systems:** (Mainzer 2007, p197) —In chaotic systems with sensitive dependence on the initial states, there is a finite loss of information for predictions of the future, according to the decay of correlations between the past states and the future state of prediction. The finite degree of uncertainty of a predicted state increase linearly to the number of steps in the future, given the entire past. But in the case of noise, the Kolmogorov-Sinai (KS) entropy becomes infinite, which means a complete loss of predicting information corresponding to the decay of all correlations. The degree of uncertainty becomes infinite.
4. "1/f spectra are typical of processes that organize themselves to a critical state at which many small interactions can trigger the emergence of a new, unpredicted phenomenon**.** Earthquakes, atmospheric turbulence, stock market fluctuations, and physiological processes of organisms are typical

examples. Self-organization, emergence, chaos, fractality, and self-similarity are features of complex systems with nonlinear dynamics…White noise is characterized by the normal distribution of the Gaussian bell curve, pink noise with a 1/f spectrum is decidedly non-Gaussian. Its patterns are footprints of complex self-organizing systems." (Mainzer 2007, p200) (A possible explanation of how wave groups and swell waves form?)

Equilibrium and Stability—there are two classes of definitions for a dynamical system: one is motivated by ordinary differential equations and is geometrical in flavour; and the other is motivated by ergodic theory and is measure theoretical in flavour. The measure theoretical assumes the existence of a measure-preserving transformation. This appears to exclude dissipative systems, as in a dissipative system a small region of phase space shrinks under time evolution.

System dynamics— is an approach to understanding the behaviour of complex systems over time. It deals with internal feedback loops and time delays that affect the behaviour of the entire system. What makes using system dynamics different from other approaches to studying complex systems is the use of feedback loops and stocks and flows. These elements help describe how even seemingly simple systems display baffling nonlinearity

Systems, Complex— See Complex systems.

Systems, Conservative— See Conservative and Dissipative Systems above.

Systems, Dissipative— See Conservative and Dissipative Systems above.

Time series analysis—See Random and Stochastic Processes section.

Volume of Fluid (VOF) Methods—The VOF model can model two or more immiscible fluids by solving a single set of momentum equations and tracking the volume fraction of each of the fluids throughout the domain. Typical applications include the prediction of jet breakup, the motion of large bubbles in a liquid, the motion of liquid after a dam break, and the steady or transient tracking of any liquid-gas interface including the dynamic free surface effect.

Wavelet Analysis —Unlike Fourier methods that determine only the frequency content of a signal, the wavelet analysis determines both the frequency and the time. This is owing to the nature of the basis functions, which are infinite for Fourier transforms (sines and cosines are infinite), but are finite for wavelet analysis (wavelets are localized waves). Wavelet analysis, and especially its generalized version—wavelet packet analysis—can successfully track spectral changes of Monte Carlo simulations.

1.1.2 Non-Deterministic Analysis

1.1.2.1 Random and Stochastic Processes

Randomness— A lack of order, purpose, cause, or predictability in non-scientific parlance. A random process is a repeating process whose outcomes follow no describable deterministic pattern, but follow a probability distribution.

Random process or **Stochastic process** —The counterpart to a deterministic process (or **deterministic system**) in probability theory. Instead of dealing only with one possible 'reality' of how the process might evolve under time (as is the case, for example, for solutions of an ordinary differential equation), in a stochastic or random process there is some indeterminacy in its future evolution described by probability distributions. This means that even if the initial condition (or starting point) is known, there are many possibilities the process might go to, but some paths are more probable and others less.

Continuous Random Process—One in which random variables which are functions of time can assume any value within a specified range of possible values.

Discrete Random Process—One in which the random variables can assume only certain specified values.

Ergodic Random Process—A stationary random process that possesses the property that almost every member of the ensemble exhibits the same statistical behaviour that the whole ensemble has. Thus, it is possible to determine this statistical behaviour by examining only one typical sample function. Such processes are said to be ergodic and the mean values and moments can be determined by time averages as well as by ensemble averages.

***Gaussian Random Process*—A** Gaussian random process with a normal density function is one of the few for which it is possible to write a joint probability density function for any number of random variables. It is also the only one for which a complete statistical analysis can be carried through in either the linear or nonlinear situations. (expand)

Non-Stationary Random Process: — All random processes which so not meet the requirements for stationarity as defined below. Unless further restrictions are imposed, the properties of a non-stationary random process are generally time-varying functions which can be determined only by performing instantaneous averages over the ensemble of sample functions forming the process. In practice, it is often not feasible to obtain a sufficient number of sample records to permit the accurate measurement of properties by ensemble averaging. (See Reference 4, page 122-) See also **Wavelet analysis.**

***Pseudo Random process*—** A process that appears random but is not. Pseudorandom sequences typically exhibit statistical randomness while being generated by an entirely deterministic causal process. Such a process is easier to produce than a genuine random one, and has the benefit that it can be used again and again to produce exactly the same numbers. This technique can be used to create an ergodic random process and is also useful for testing and fixing software.

Stationary Random Process—If all marginal and joint density functions of the process do not depend upon the choice of time origin, the process is said to be stationary. A process for which the mean variances, covariance functions and probability densities are independent of time translations. Thus Fourier transform pairs for a stationary random process are well defined.

Time Series Analysis (Mainzer 2007 p78, p338*)* —A bottom-up approach that aims to construct a black box, which takes the measured data as input and provides as output a mathematical model describing the data. However, it is rather difficult to reconstruct an underlying attractor and its dimension d. For chaotic systems with d>3, it is a challenge to distinguish between a chaotic time evolution and a random process, especially if the underlying deterministic dynamics are unknown.

1.1.2.2 Probability and Statistics

Bayesian probability (Wikipedia) — One of the most popular interpretations of the concept of probability. The Bayesian interpretation of probability can be seen as an extension of logic that enables reasoning with uncertain statements. To evaluate the probability of a hypothesis, the Bayesian probabilistic specifies some prior probability, which is then updated in the light of new relevant data. The Bayesian interpretation provides a standard set of procedures and formulae to perform this calculation.

Bayesian analysis — Requires evaluating expectations of functions of random quantities as a basis for inference, where these quantities may have posterior distributions which are multivariate or of complex form or often both. This meant that for many years Bayesian statistics was essentially restricted to conjugate analysis, where the mathematical form of the prior and likelihood are jointly chosen to ensure that the posterior may be evaluated with ease. Numerical integration methods based on analytic approximations or quadrature were developed in 70's and 80's with some success, but a revolutionary change occurred in the early 1990s with the adoption of indirect methods, notably Markov Chain Monte Carlo (MCMC).

Bayes' theorem —Adjusts probabilities given new evidence in the following way:

$$P(H|D) = \frac{P(D|H)P(H)}{P(D)}$$

where

- H is a hypothesis, and D is the data.
- $P(H)$ is the *prior probability* of H: the probability that H is correct before the data D was seen.
- $P(D \mid H)$ is the conditional probability of seeing the data D given that the hypothesis H is true. $P(D \mid H)$is called the *likelihood*.
- $P(D)$ is the marginal probability of D.
- $P(H \mid D)$ is the *posterior probability*: the probability that the hypothesis is true, given the data and the previous state of belief about the hypothesis.
- $P(D)$ is the prior probability of witnessing the data D under all possible hypotheses. Given any exhaustive set of mutually exclusive hypotheses Hi, we have:
-

$$P(D) = \sum_i P(D, H_i) \sum_i P(D|H_i)P(H_i).$$

We can consider i here to index alternative worlds, of which there is exactly one which we inhabit, and Hi is the hypothesis that we are in the world i. $P(D,H_i)$ is then the probability that we are in the world i and witness the data. Since the set of alternative worlds was assumed to be mutually exclusive and exhaustive, the above formula is a case of the law of alternatives.

$P(D)$ is the normalizing constant, which in many cases need not be evaluated. As a result, Bayes' formula is often simplified to:

$$P(H|D) \propto P(D|H)P(H)$$

where ∀ denotes proportionality.

In general, Bayesian methods are characterized by the following concepts and procedures:

- The use of hierarchical models, and the marginalization over the values of nuisance parameters. In most cases, the computation is intractable, but good approximations can be obtained using Markov chain Monte Carlo methods.
- The *sequential use of the Bayes' formula*: when more data becomes available after calculating a posterior distribution, the posterior becomes the next prior. Example: analysis of space launch failure rate as launches progress including analysing near misses.
- In frequentist statistics, a hypothesis is a proposition (which must be either true or false), so that the (frequentist) probability of a frequentist hypothesis is either one or zero. In Bayesian statistics, a probability H represents a specific hypothesis, which may or may not be some null hypothesis.

Central Limit Theorem: — States that the sum of a large number of independent and identically-distributed random variables will be approximately normally distributed (i.e., following a Gaussian distribution, or bell-shaped curve) if the random variables have a finite variance. Formally, a **central limit theorem** is any of a set of weak-convergence results in probability theory. They all express the fact that any sum of many independent identically distributed random variables will tend to be distributed according to a particular "attractor distribution".

Conditional Probability —The probability of some event A, given the occurrence of some other event B. Conditional probability is written $P(A|B)$, and is read "the probability of A, given B".

Conditioning of probabilities —Updating them to take account of (possibly new) information, may be achieved through Bayes' theorem. In such conditioning, the probability of A given only initial information I, $P(A|I)$, is known as the prior probability. The updated conditional probability of A, given I and the outcome of the event B, is known as the posterior probability, $P(A|B,I)$.

Confidence interval —A range that contains the true value of mean value, variance, or any other probabilistic characteristic, with a given confidence probability β.

Joint Probability—The probability of two events in conjunction. That is, it is the probability of both events together. The joint probability of *A* and *B* is written *P(A∩B) or P(A,B).*

Kurtosis (from the Greek word κυρτός, *kyrtos* or *kurtos*, meaning bulging) **—**A measure of the "peakedness" of the probability distribution of a real-valued random variable. Higher kurtosis (leptokurtic distribution) means more of the variance is due to infrequent extreme deviations, as opposed to frequent modestly-sized deviations.

Marginal Probability —The unconditional probability *P*(*A*) of the event *A*; that is, the probability of *A*, regardless of whether event *B* did or did not occur. If *B* can be thought of as the event of a random variable *X* having a given outcome, the marginal probability of *A* can be obtained by summing (or integrating, more generally) the joint probabilities over all outcomes for *X*. For example, if there are two possible outcomes for *X* with corresponding events *B* and *B′*, this means that *P(A) = P(A∩B) + P(A∩B′).* This is called **marginalization.**

Mean — In statistics, mean has two related meanings: (1) the arithmetic mean (and is distinguished from the geometric mean or harmonic mean). (2) the expected value of a random variable, which is also called the population mean.

Normal Distribution — In probability theory, the **normal** (or **Gaussian**) **distribution** is a continuous probability distribution that is often used as a first approximation to describe real-valued random variables that tend to cluster around a single mean value. The graph of the associated probability density function is "bell"-shaped, and is known as the *Gaussian function* or *bell curve*:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}},$$

where parameter μ is the *mean* (location of the peak) and σ^2 is the *variance* (the measure of the width of the distribution). The distribution with μ = 0 and σ^2 = 1 is called the **standard normal.** The normal distribution arises as the outcome of the central limit theorem, which states that under mild conditions the sum of a large number of random variables is distributed approximately normally. Finally, the "bell" shape of the normal distribution makes it a convenient choice for modeling a large variety of random variables encountered in practice.

Non-normal Distribution — The possibility should be considered that the underlying distribution of the data is not approximately normal, and may have "fat tails". For instance, when sampling from a Cauchy distribution, the sample variance increases with the sample size, the sample mean fails to converge as the sample size increases, and outliers are expected at far larger rates than for a normal distribution.

Probability Density function — In probability theory, a probability density function or density of a continuous random variable is a function that describes the relative likelihood for this random variable to occur at a given point. The probability for the random variable to fall within a particular region is given by the integral of this variable's density over the region. The probability density function is nonnegative everywhere, and its integral over the entire space is equal to one. Not every probability distribution has a density function: the distributions of discrete random variables do not; nor does the Cantor distribution, even though it has no discrete component, i.e., does not assign positive probability to any individual point.

Probabilistic risk assessment (PRA) (or **probabilistic safety assessment/analysis**) —A systematic and comprehensive methodology to evaluate risks associated with a complex engineered technological entity (such as an airliner or a nuclear power plant).

Probability of Occurrence: — The likelihood or chance that a particular event will occur due to exposure of the ship to specified wave and wind conditions for a specified period of time. The Probability of Occurrence for a wave-induced motion or hydrodynamic loading is expressed numerically as $1x10^{-n}$, for 10^{m} hours of exposure, with an xx% confidence limit (uncertainty), for wave conditions with an assumed spectrum of wave heights and modal periods. The values for "n", "m", "xx" and the description of the assumed wave spectra (e.g., Pierson-Moskowitz) must be specified.

Rayleigh Distribution — A continuous probability distribution. It can arise when a two-dimensional vector (e.g. stationary irregular wave height and direction) has elements that are normally distributed, (wave elevation) are uncorrelated, and have equal variance. The vector's magnitude (e.g. wave height) will then have a Rayleigh distribution. The distribution can also arise in the case of random complex numbers whose real and imaginary components are i.i.d. Gaussian. In that case, the modulus of the complex number is Rayleigh-dis*tributed.*

Statistical Independence — In probability theory, to say that two events are **independent,** intuitively means that the occurrence of one event makes it neither more nor less probable that the other occurs. Similarly, two random variables are independent if the conditional probability distribution of either given the observed value of the other is the same as if the other's value had not been observed. **See also Complex Systems: Loose coupling and tight coupling.**

Weibull Distribution.—A two parameter it can mimic the behavior of other statistical distributions such as the normal and the exponential. If the failure rate decreases over time, then $k < 1$. If the failure rate is constant over time, then $k = 1$. If the failure rate increases over time, then $k > 1$.

1.1.3 Uncertainty and Risk

From Wikipedia:

1. **Uncertainty**: — The lack of certainty, A state of having limited knowledge where it is impossible to exactly describe existing state or future outcome, more than one possible outcome.
11. **Measurement of Uncertainty**: — A set of possible states or outcomes where probabilities are assigned to each possible state or outcome - this also includes the application of a probability density function to continuous variables.
12. **Risk**: — A state of uncertainty where some possible outcomes have an undesired effect or significant loss.
13. **Measurement of Risk**: — A set of measured uncertainties where some possible outcomes are losses (failures), and the magnitudes of those losses - this also includes loss functions over continuous variables.

Uncertainty Analysis (ITTC) —Measurement uncertainty results may be grouped in 2 categories called Type A uncertainty and Type B uncertainty. They are defined as follows:

Type A Uncertainties are those evaluated by applying statistical methods to the results of a series of repeated measurements. The components in type A uncertainty are defined by the estimated variance, which includes the effect of the number of degrees of freedom (DOF).

Type B Uncertainties are those evaluated by other means. The definition has been further refined by ISO (1995) to include prior experience and professional judgments, manufacturer's specifications, previous measurement data, calibrations, and reference data from handbooks. The components in type B uncertainty are also approximated by a corresponding variance, in which its existence is assumed.

The combined Uncertainty should be computed by the normal method for the combination of variances, now known as the law of propagation of uncertainty. For particular applications, the combined uncertainty should be multiplied by a coverage factor to obtain an overall uncertainty value. The overall uncertainty is now called expanded uncertainty. For the 95 % confidence level, the commonly applied coverage factor is 2.

Code Verification and Validation (Freitas 2006, Stern 2007) —Verification is a process to establish and confirm accuracy. In the context of numerical simulation, we wish to establish and confirm the accuracy of a numerical model of a physical system. A numerical model consists of the code and the solution to a specific problem. The verification process for a numerical model must then establish and confirm accuracy for both the code and the solution. Code verification is distinct from Solution verification and must precede it, even though both procedures utilize grid convergence studies. In general, code verification assesses code correctness and specifically involves error evaluation for a known solution. By contrast, solution verification involves error estimation, since we do not know the exact solution to the specific problem. Code and solution verification are mathematical activities, with no concern whatever for the agreement of the numerical model with physical data from experiments, that is the concern of validation. Note, however, that the solution and its error estimation from solution verification will be used in the validation process. In this way, code verification, solution verification, and validation are coupled together into an overall process.

1.1.3.1 Validity and Reliability of Engineering Analytical Methods & Processes

(Prepared by Professor Bob Bea) Engineering analytical methods and processes and changes (suggestions, recommendations) implicated by such processes should be valid and reliable. **How can the properties of validity and reliability be determined?**

A reliable method is one that yields valid and consistent results upon repeated use. A reliable method is suitable for its intended purposes. Reliability is established through multiple applications in prototype conditions by independent and qualified users representative of those that will use the method in practice.

Valid—being supported by objective truth or generally accepted authority, based on flawless reasoning and solid ground, well grounded, sound, having a conclusion correctly derived from premises, cogent, convincing.

Reliable — suitable or fit to be relied upon, trustworthy, worthy of full confidence, dependable. Campbell and Stanley (1963) have addressed the approaches that can be used to establish the validity of engineering analytical methods and processes. **There are two approaches:**

1. External Validity is the extent to which the method (approach) is generalizable or transferable. A method's generalizability is the degree the results of its application to a sample population can be attributed to the larger population. A method's transferability is the degree the method's results in one application can be applied in another similar application.

2. Internal Validity is the basic minimum without which the method is uninterpretable. Internal validity of a method addresses the rigor with which a method is conducted - how it is designed, the care taken to conduct measurements, and decisions concerning what was and wasn't measured. There are four different types of internal validity: 1) face, 2) content, 3) criterion-related, and 4) construct.

Face Validity— The degree to which a method appears to be appropriate for doing what it intends to do. Face validity is based on justifications provided by the state-of-art and state-of-practice knowledge and experience.

Content Validity—addresses the degree to which the method addresses the problem (issue) it is intended to address.

Criterion Validity—addresses the degree to which the method allows for assessment of an issue or problem beyond the testing situation; the generalizability of the method. Criterion validity may be concurrent or predictive; the evaluation may be either be intended to assess a criterion independently evaluated at the same time (concurrent), or to predict achieving a criterion in the future (predictive).

Construct Validity—addresses the degree to which the results of the method can be accounted for by the explanatory constructs of a sound theory. A method's construct validity can be assessed by specifying the theoretical relationships between the concepts and then examining the empirical relationships between the measures of the concepts, and then interpreting how the observed evidence clarifies the concepts being addressed. Construct validity is demonstrated when measures that are theoretically predicted to be highly interrelated are shown in practice to be highly interrelated.

Reference: Campbell, D. T. and Stanleny, J. C. (1963): ***Experimental and Quasi-Experimental Design for Research***, Houghton Mifflin, Co., Boston.

3. Complex Systems including Complex Failures

Bounded Rationality (Mainzer, 2007 p334) —The capacity of the human mind for formulating and solving complex problems is very small compared with the size of the problem whose solution is required for objectively rational behavior in the real world or even for a reasonable approximation to such objective rationality

1.1.4 Principal Definitions

Complex System—(Wikipedia) A system composed of interconnected parts that as a whole exhibit one or more properties (behaviour among the possible properties) not obvious from the properties of the individual parts. A system's complexity may be of one of two forms: disorganized complexity and organized complexity. In essence, disorganized complexity is a matter of a very large number of parts, and organized complexity is a matter of the subject system (quite possibly with only a limited number of parts) exhibiting emergent properties.

Complex adaptive Systems (CAS) — are special cases of complex systems. They are complex in that they are diverse and made up of multiple interconnected elements and adaptive in that they have the capacity to change and learn from experience.

Complex Systems (CS) — A category that includes most physical systems beyond the simple category such as human-conceived production systems, weather models, various economic systems, and models and simulations of real dynamic systems whose behavior depends on a complex set of rules and constraints. Complex Systems can be either deterministic or non-deterministic (probabilistic) or a combination of both. The nature of the forcing functions impacts on this distinction.

Complex Adaptive Systems *(CAS)* — include intelligent systems and rule-based simulations that self-organize by learning and/or adapting to new classifier (pattern recognition) rules.

Interactive Complexity (Bookstaber, 2007) — is a measure of the way the components of a system connect and relate. An interactively complex system is one whose components can interact in unexpected or varied ways, where there is feedback that can lead the components to differ in their state or their relationship with the rest of the system from one moment to the next, where the possible stages and interactions are not clearly apparent or cannot be readily anticipated. Systems with high levels of interactive complexity are subject to failures that seem to come out of nowhere or that appear unfathomably improbable (Black Swan events, Taleb, 2007).

Loose Coupling — Loose coupling means that the component failures of a linear system can be considered as having independent probabilities and thus joint probabilities are computable.

Tight Coupling (Bookstaber, 2007) —Tight coupling means that components of a process are critically interdependent and thus non-Gaussian. They are linked with little room for error or time for recalibration or adjustment. A process that is tightly coupled can be prone to accidents even if it is not complex. It can also be applied to a time-driven system in which one event leads to another in short order, i.e. a chain accident with no time to correct the actions. Other system failures grow out of a chain or errors and mishaps over time without the operators discovering the source of the misinformation as was the case for the Three Mile Island accident.

1.1.5 Failure Modes of Complex Systems

Complex system failures can be classified by type:

Common Cause Failure — defined as a specific condition which may result in a single failure event and which would be capable of causing each element of channel of a redundant system to fail.

***Critical period* —**Multiple failures though common cause of elements of a redundant system will result in overall systems failure if they occur within a time interval known as the critical period.

Non-concurrency* —:* When multiple failures through common cause of elements of a redundant system occur over a given time interval greater than the critical period, the individual element are said to be non-concurrent. System failure in non-concurrency mode is capable of prevention by human intervention or scheduled changes in process operation. (Mediation)

Common Mode Failure — In technical facilities, for example in nuclear power plants and commercial aircraft, redundant systems are used to prevent random failures from deleting the complete system function. However, although this redundancy concept is adequate to cope with random failures in single redundancies, its applicability is limited in case of multiple failures due to a systematic failure cause to which all redundancies are submitted due to their identical features. Some general considerations have been formulated to rule out the occurrence of such common mode failure (CMF) in redundant systems under certain circumstances. CMF means that in more than one redundancy the systematic failure cause is activated at the same time, or within the same frame of time (e.g. during the mission time for an accident)

Cascade Failure — A failure in a system of interconnected parts in which the failure of a part can trigger the failure of successive parts. They occur in power system grids, computer networks, vessel capsizes involving impaired stability**.** System failure in non-concurrency mode is capable of prevention by human intervention such as the USCG delivering a dewatering pump to a fishing vessel taking on water. In finance systems, where the risk of cascading failures of financial institutions is referred to as *systemic risk:* the failure of one financial institution may cause other financial institutions (its counterparties) to fail, cascading throughout the system. Institutions that are believed to pose systemic risk are deemed either "too big to fail" (TBTF)

Independent Failure vs. Dependent Failure — The overriding problem in risk assessment is to differentiate between the dependent failure and that of the independent failure. It is much simpler to predict the frequency of independent failures for which the probabilities are knowable. Dependent failures involve conditional probabilities which are much more complex. To this end there have been many modeling methods, mostly theoretically based, which lack a practicable engineering approach to a satisfactory understanding and solution.

Normal Accident (Perrow, 1999) — The cascade of failure that occurs in systems that share tight coupling and complexity gives rise to what are called normal accidents.' As ironic as the term sounds, normal accidents are accidents that are to be expected; they are an unavoidable result of the structure of the process. The more complex and tightly coupled the system, the greater the frequency of normal accidents. The probability of any one event is small enough to be dismissed, but taken together, with so many possible permutations and with combinations beyond comprehension, the odds of one or the other happening are high.

Note also that a normal accident sequence involving potential loss of life can be interrupted by lucky human intervention. These involve non-computable probabilities such as having an experienced glider pilot at the controls of a commercial aircraft struck in both engines by birds. Examples of non-interrupted accident sequences: capsizing caused by being in the wrong place (i.e. the focal point of a rogue wave or microburst) at the wrong time (when it breaks or strikes) even if the vessel satisfies existing stability criteria.

Normal accidents include rare events which are frequently called *Black Swan* events in the popular press. These events lie outside the realm of regular expectations, because nothing in the past can convincingly point to its possibility. Second, it carries an extreme impact. Third, in spite of its outlier status, human nature makes us concoct explanations for its occurrence after the fact, making it explainable and predictable. Tight coupling system failures are generally rare, previously not experienced and involve unknown but non-zero retrospective probabilities. Examples: penetrating the Maginot Line in 1940; the 9/11/2001 terrorist attacks; the consequences of the Pacific tsunamis of December 2004 and March 2011 and so on. Note: these examples may be normal accidents to knowledgeable persons in particular disciplines who recognize that such tightly coupled events have non-zero probabilities which are not computable. Actually, the majority of normal accidents arise from non-repeating sequences of events. These events can be analysed using statistical hindcasts (a weather term) for modification to assumed “fat-tail” probabilities, but not accurately forecast since this new sequence of events has never happened before. Note the different sequences in the Market Crashes of 1987 and 2008, the oil drilling spill of 1979 and 2010, and the accidents involving the space shuttles Columbia and Challenger.

Scenario Analysis— see Scenario analysis in Section 1.2

4. Liquid properties and physical constants

Under this heading definitions or descriptions are given of a number of liquid properties and physical constants concerned of ship hydrodynamics.

Capillarity (phenomenon) — A form of surface tension, by which a molecular force exists between the surface of a liquid and a solid. The surface of the liquid may thereby be elevated or depressed.

Capillarity (σ) [M T^{-2}] — Surface tension per unit length.

Compressibility, coefficient of (-) [LM^{-1} T^2] — The reciprocal of the volume or bulk modulus of elasticity. (See: *Modulus of elasticity, volume or bulk*)

Density, mass (ρ) [L^{-3} M**]** — The mass per unit volume of a substance. *

Density, weight (w) [L^{-2} M T^{-2}] — The weight per unit volume of a substance.

Gravitational acceleration (g) [L T^{-2}] —The acceleration, due to earth's gravity field, of a freely falling body in a vacuum. This is not strictly constant\and over the earth's surface it varies by as much as ½%. For most terrestrial engineering purposes it is usual to disregard this variation and for convenience the following international standard value has been agreed: 9.80665 m/s^2 (32.1737 ft/s^2).

Modulus of elasticity, volume or bulk (E) [L^{-1} M T^{-2}] —The ratio of the stress, or force per unit area, to the corresponding change of volume per unit volume.

Relative mass or weight (γ) [-]— The ratio of density of any substance to the density of fresh water at 4° Centigrade. In English speaking countries the concept expressed is called Specific gravity.

Solubility — The relative capability of being dissolved.

Specific volume (L^3M^{-1}) —The volume of a substance per unit mass; the reciprocal of mass density (See: Density, mass)

Specific weight or specific gravity (-) [-]— See: *Relative mass or weight*.

Surface tension —The property of the interface between two immiscible fluids of behaving as if it were a film under tension.

Vapour pressure —The pressure of vapour in equilibrium with its liquid state. It is also called the saturated vapour pressure or vapour tension, which for a given substance depends only upon the temperature.

Viscosity, coefficient of dynamic (μ) [L^{-1} M T^{-1}]* — The ratio of the shearing stress in a fluid to its rate of shear deformation. See also: *Resistance section*.

Viscosity, coefficient of kinematic (ν) [L^2 T^{-1}]* The ratio of the coefficient of dynamic viscosity to the mass density of a fluid. See also: *Resistance section*.

* For standard values of fresh water and salt water at 15° C (59° F) see: *Performance Section* under "Water standard fresh and salt". For values over a range of temperature in S.I units see in "Metrication Ship Research and Design", Paffett, J.A.H. Trans. RINA, 1971; for corresponding values in Imperial Unit see Proceedings 10th International Towing Tank Conference, London 1963 or National Physical Laboratory, Ship Division Report No. 81 (1966).

2. VESSEL GEOMETRY AND STABILITY

This section is concerned with vessel and hull geometry generally. Propeller geometry is given in the Propeller Section.

5. Vessel Geometry and Hydrostatics

Amidships (sometimes contracted to midship) (⨂) [-]—Near the centre of ship length, specially, the section of the ship at mid length.

Angle of entrance —See: *waterline.*

Angle of run —See: *waterline.*

Angle, deadrise (β) [rad] —See: *Deadrise angle*.

Appendage —An additional structure or fitting to the main underwater hull of a ship, which generally results in a discontinuity in the fair surface of the main hull. Examples of appendages are: rudders, bossings, struts, shafts, bilge keels, stabilizing fins, etc. (See appropriate items)

Area, bulbous bow in longitudinal plane (A_{BL}) [L^2] —The area of the ram projected onto the centreplane forward of the fore perpendicular.

Area, transverse cross section of a bulbous bow (A_{BT}) [L^2] — The cross sectional area (full section port and starboard) at the fore perpendicular. Where the water lines are rounded so as to terminate on the fore perpendicular A_{BT} is measured by continuing the area curve forward to the perpendicular, ignoring the final rounding.

Area, maximum section (A_X) [L^2] —See: *Section.*

Area, midship section, or midlenght section (A_M) [L^2] —See: *Section*.

Area, planning bottom (A_{PB}) [L^2] — Horizontally projected planning bottom area (at rest), excluding area of external spray strips (See Figure 2-1).

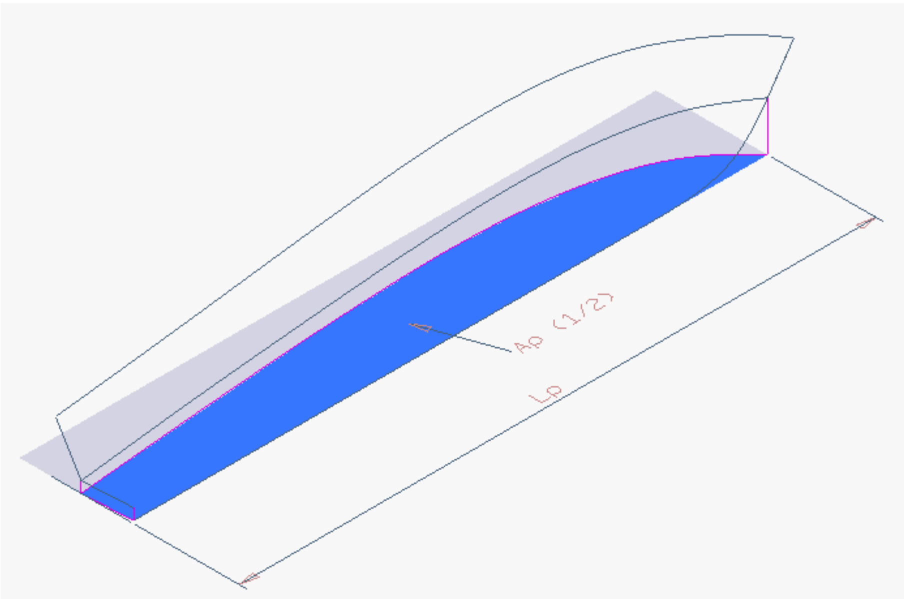


Figure 2-1: Planing bottom area.

Area, wind exposed (A_V) [L^2] —Area of the portion of ship above the waterline projected to the direction of relative wind.

Aspect ratio —See: *Manoeuvrability Section.*

Baseline —The intersection of the baseplane with the centerplane (see Figure 2-2). **NOTE This definition deviates from the ISO Definition.**

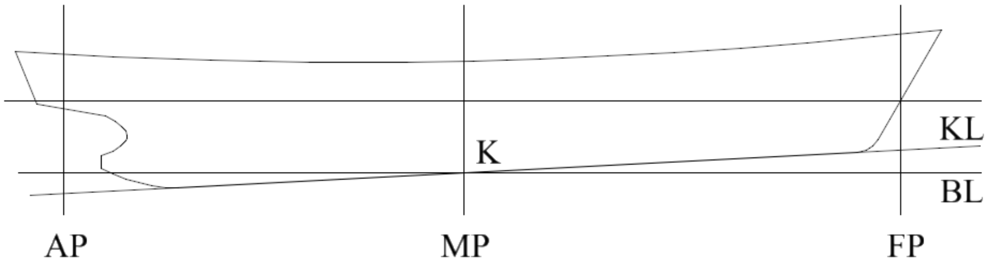


Figure 2-2: Baseline and Keel Line.

Baseplane —See: *Planes, principal co-ordinate.*

Beam (B) [L] —A dimension expressing breadth or width of a body or ship in a transverse horizontal direction. When not otherwise defined the beam is the breadth moulded of a ship, measured amidships at the design waterline. According to the position where the breadth is measured, it is named: **NOTE This definition deviates from the ISO Definition.**

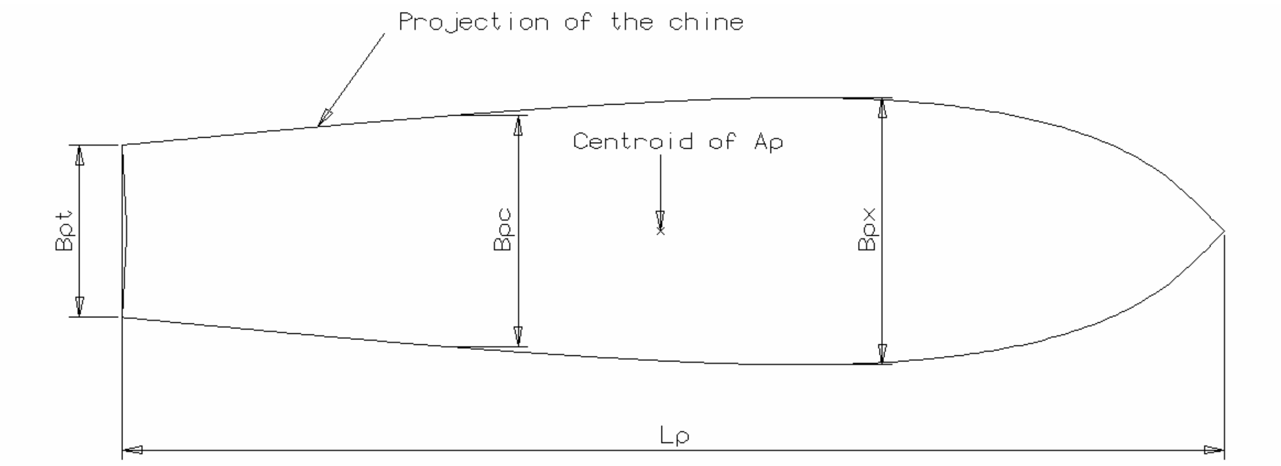


Figure 2-3a: Beam (Breadth) definitions for a hard chine hull.

Beam, extreme: — maximum beam wherever it occurs on the hull above or below water.

Beam, immersed: —maximum: maximum beam of underwater body.

Beam, maximum section — (B_X): beam measured on the designed waterline at the maximum section area.

Beam, midlenght (B_M): —beam at the midsection of the designed waterline.

Beam of design water line (B_{WL}) [L]: — maximum moulded breadth at design water line for a hard chine hull the beam refers to the breadth or width of the planning bottom. According to the position where the breadth is measured, it is named:

Beam, over chines (B_{PC}) [L]: — beam over chines, excluding external spray strips (See Figure 2-3a).

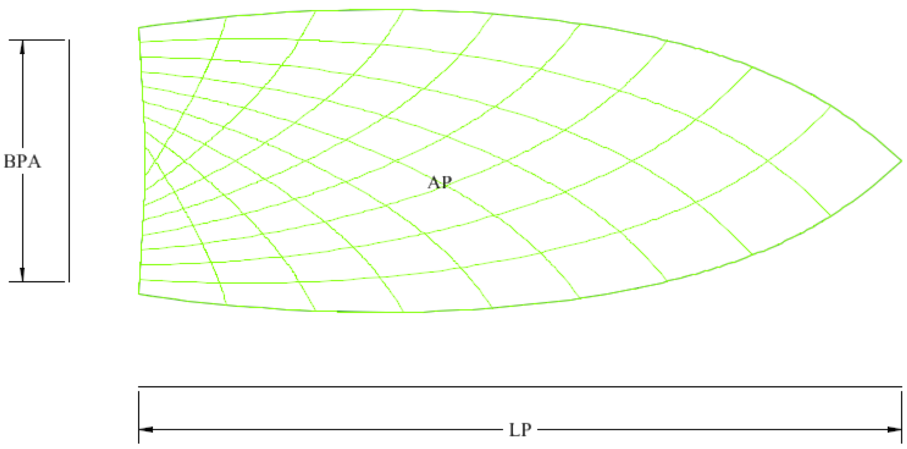


Figure 2-3b: Mean beam over chines.

Beam, mean over chines (B_{PA}) [L]: — mean breadth over chines; defined as the ratio between planning bottom area and projected chine length. (See Figure 2-3b)

$$B_{PA} = \frac{A_{PB}}{L_{PR}}$$

Beam, transom (B_{PT}) [L]: —Breadth over chines at transom, excluding external spray strips (See Figure 2-3a).

Beam, maximum over chines (B_{PX}) [L]: — Maximum breadth over chines, excluding external spray strips (See Figure 2-3a).

Bilge —The submerged transversally curved portion of the ship between the side and bottom. This region is also called the turn of the bilge. The minimum radius of the bilge at the section of maximum area is called bilge radius.

Bilge keel —See: *Keel.*

Block coefficient (C_B, formerly δ) [-]—The ratio of displacement volume ∇ to the volume of a rectangular block having length L, beam equal to the waterline beam B_X and draught T_X:

$$C_B = \frac{\nabla}{L B_X T_X}$$

If it is referred to length, beam or draught other than those defined above, they should be clearly defined.

Body —Any hull or form which may be immersed or floating in a fluid, if a ship, usually its underwater portion. Particular parts of the body of a ship are:

Forebody: —the part forward of the midsection

Afterbody: —the part aft of the midsection

Parallel middle-body, length of, (L_P): — the midship portion having the same transverse section throughout.

Entrance, length of, (L_E): — the portion extending from the maximum area section, or from the fore end of the parallel middle-body, to the forward extremity of the underwater body.

Run, length of, (L_R): — that portion extending from the maximum area section, or from the after end of the parallel middle-body, to the after extremity of the underwater body. See Figure for illustrations of these items.

Body plan —The transverse sections of the ship projected on to a vertical transverse plane. The sections are generally equally spaced.

Bossing —The part of the underwater hull of a ship which is carried outward beyond the fair form to enclose the propeller shafts or other external items. Bossings are of two general forms:

i. Short— intended only to house the aftermost hull bearing of a propeller shaft or to form a faring where the propeller shaft emerges from the hull.

ii. Long— enclosing the entire propeller shaft, shaft bearings, and the supporting frame from the hull to the propeller.

A long bossing is called contra or deflection type when its end is shaped to direct the flow of water against the direction of rotation of propeller (See Figure 2-4).

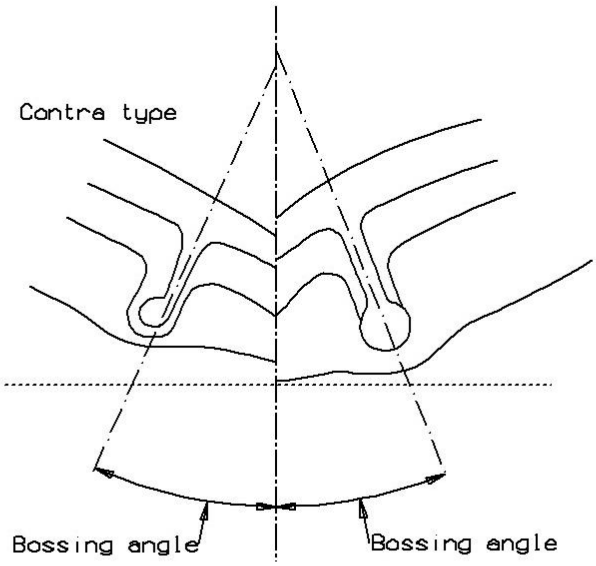


Figure 2-4: Propeller shaft bossings.

Bossing, angle —Angle of bossing with the plane of symmetry (See Figure 2-4).

Boundary plate —A plate at, or near, the tip of a hydrofoil, or of an element acting as a hydrofoil, to suppress or reduce the tip vortex.

Bow —The forward end of a ship.

Bowline —Intersection of a plane parallel to the centre plane with the moulded form of the forebody of the ship, both above and below the waterline. Similar intersections in the afterbody are called buttocks.

Breadth —A length dimension expressing beam or width in a transverse horizontal direction. (See: *beam*) The ISO prefers this nomenclature.

Breadth coefficient of, R.E: Froude (B_C) [-]—The ratio of the maximum breadth to the cube root of the volume displacement of a ship.

$$B^{C} = \frac{B_X}{\nabla^{1/3}}$$

in a consistent system of units.

Breakwater —A protection erected on the weather deck, generally forward, normally V-shape in planform, to prevent water shipped over the bow from running aft.

Bulb —An appreciable swelling of the ship form generally below the waterline, involving increase of section area; frequently at the forward end lying just above the keel (bulbous bow), sometimes with increase of length beyond the forward perpendicular (ram bulb), sometimes the after end near the keel or at the level of the propeller shaft (stern bulb). The ram bulb dimensions are characterised by the transverse cross section area at the fore perpendicular (A_{BT}), and the ram area in the longitudinal plane (A_{BL}), which is the area of ram ahead of the fore perpendicular projected on to the centerplane. In non-dimensional form:

Taylor sectional area coefficient for bulbous bow (f_{BT}) [-]: —

$$f_{BT} = \frac{A_{BT}}{A_X}$$

Area coefficient for ram bow (f_{BL}) [-]: —

$$f_{BL} = \frac{A_{BL}}{LT}$$

When the waterlines are rounded so as to terminate on the forward perpendicular, A_{BT} is measured by continuing the area curve forward to the perpendicular, ignoring the final rounding. In some instances, the stem contour recedes aft the fore perpendicular below the load waterline before projecting forward to define the outline of the ram or fore end of the bulb. In such instances this area should be calculated using as datum the aftermost vertical tangent to the contour instead of the fore perpendicular.

Buoyant Volume — The watertight volume of a vessel.

Note: USCG NVIC 5-86: **—** Deckhouses should be included in the buoyant volume only if:

a. They are of substantial construction so that they can withstand the impact forces of waves,

b. They have internal access to the spaces below; otherwise, it should be assumed that the exterior doors will be used for access, thus disrupting the buoyant envelope watertight integrity.

c. All openings in the sides of the deckhouse are weathertight. (NOTE: Joiner doors should not be considered as weathertight.),

d. All windows have deadlight covers. In general, volumes which are watertight and of sufficient strength are fully effective. The Coast Guard recommends that all fully effective volumes be included in the buoyant volume for the righting arm calculations. Although the exclusion of these volumes may be more conservative, using the allowed buoyant volumes permits a more accurate assessment of the vessel's stability characteristics.

Buttock —The intersection of a plane parallel to the centreplane with the moulded form of the ship, both below and above the waterplane. Specifically, all such intersections in the afterbody, as distinguished from similar intersections in the forebody, called bowlines.

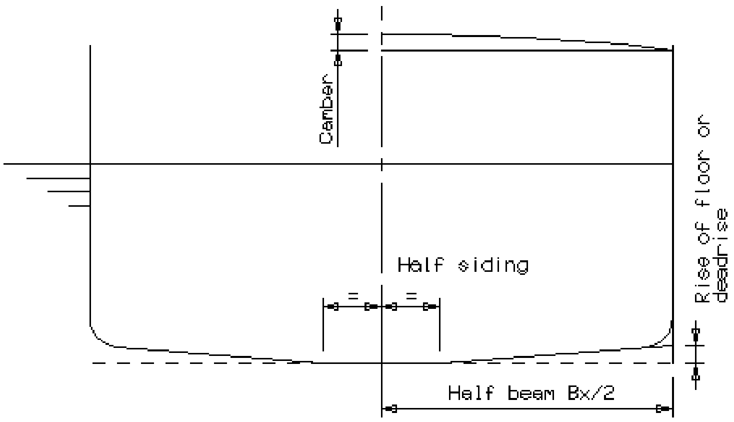


Figure 2-5: Camber at a midships section.

Camber—Generally applied to decks, where it represents the curvature in an athwartship or transverse vertical plane; the height of the deck at the centreline above the height at side. (See Figure 2-5).

Camber (of a foil section) (*f*) [L] —The maximum separation of the mean line and nose-tail line. (See Figure 2-6 and Figure 4-7).

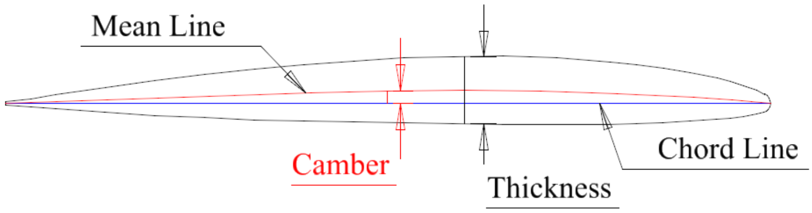


Figure 2-6: Blade section characteristics.

Centre of buoyancy (B) [-]—The geometric centroid, B of the submerged volume of a body or ship through which the total buoyancy may be assumed to act. Its position, measured as the distance from midship or from the fore ($\overline{FB}$) or after perpendicular ($\overline{AB}$) is called the *Longitudinal centre of buoyancy* and from the base line or keel ($\overline{KB}$) the *Vertical centre of buoyancy*. In non dimensional form these distances are often expressed as ratios of length of the ship $\overline{FB}/_L$ or $\overline{AB}/_L$, and of the draught $\overline{KB}/_T$ respectively.

Centre of flotation (F) [-]—The geometric centroid of the area of waterplane of any waterline. Its position measured as the distance from midships or from the fore or after perpendicular, is called *Longitudinal centre of flotation*, and is generally expressed as a ratio of the waterline length.

Centre of gravity (G) [-]—The centre through which all the weights constituting the ship and its contents may be assumed to act. The distance measured from midships, from the fore perpendicular ($\overline{FG}$) or from the after perpendicular ($\overline{AG}$), and from the baseline or keel ($\overline{KG}$) are called *Longitudinal and Vertical centre of gravity* respectively. They are generally expressed as ratios of the ship length $\overline{FG}/_L$ or $\overline{AG}/_L$ and of the ship depth $\overline{KG}/_D$ respectively.

Centreplane —See: *Planes, principal, co-ordinate*.

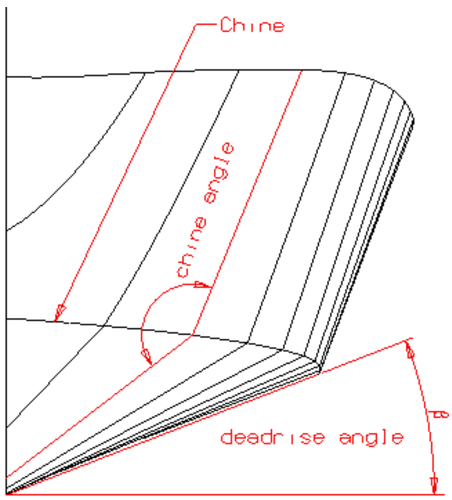


Figure 2-7**:** Hull form with chine.

Chine (See Figure 2-7) —A more or less sharp corner or knuckle in the hull form, continuous over a significant length of the ship, as in the junction of side and bottom in planning craft. The chine is known as “soft” when the corner is rounded, and “hard” otherwise.

Chine angle (See Figure 2-7) —The angle at the junction between the two parts of a section, on either side of a chine or the angle between the tangents to these two parts, measured in a transverse plane.

Chine line (See Figure 2-7) —The actual (in a "hard" chine), or imaginary (in a "soft" chine), locus of the intersections of the two parts of the hull form at the chine.

Chord (of a foil section) (c) [L] —The length of the chord line which is the straight line connecting the extremities of the mean line of a hydrofoil section. It passes through, or nearly through, the fore and aft extremities of the section. Synonymous with nose-tail line (see also Figure 2-6).

Clearances, propeller (See Figure 2-8) —The clearances as indicated between the sweep line of a propeller and the hull or aperture in which is placed. As shown, the fore and aft clearances are generally measured at 0.70 of the propeller radius above and below the shaft centreline.

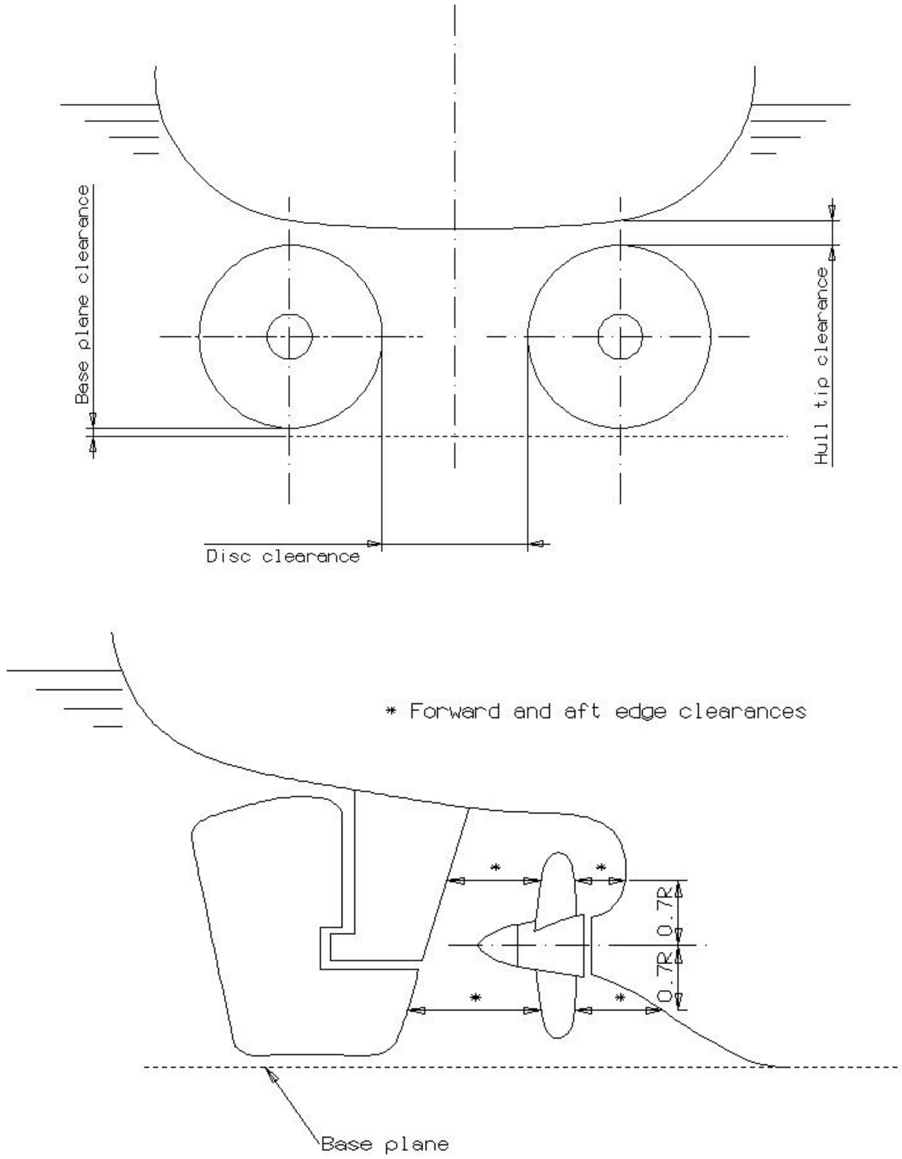


Figure 2-8: Propeller clearances.

Coefficient, block — See: *Block coefficient*.

Coefficient, prismatic —See: *Prismatic coefficient*.

Coefficient, prismatic, vertical —See: *Prismatic coefficient, vertical*.

Coefficient, maximum transverse and midship section —See: *Sectional area coefficient*.
Coefficient, waterplane, designed load —See: *Waterplane coefficient, designed load*.
Coefficient, waterplane, inertia —See: *Waterplane inertia coefficient*.
Counter —The overhanging portion of stern of a ship which lies between the designed waterplane and deck and which project abaft the waterline termination. See also *Stern, Counter* or *Fantail* and Figure 2-25 a).
Cutaway (See Figure 2-9) — A volume cut out of a body, specifically at the forward or after end of a ship.

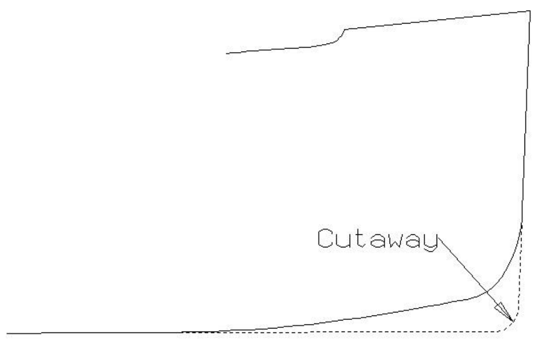


Figure 2-9: Cutaway at fore end of ship.

Cutwater —A narrow sharp portion of the stem of a ship at the waterline, or an appendage added to the stem to reduce the spray.
Deadrise angle (β) [rad] —Angle between a straight line approximating the bottom part of a body section and the intersection between basis plane and section plane (See Figure 2-7). According to the position were the deadrise angle is measured, it is named:
Deadrise , angle at midship (β_M) [rad]: — deadrise angle at midship section
Deadrise , angle at transom (β_T) [rad]: — deadrise angle angle at transom See also: *Floor, rise of - or deadrise.*
Deadwood —Figure 2-10 (See also *Skeg).*

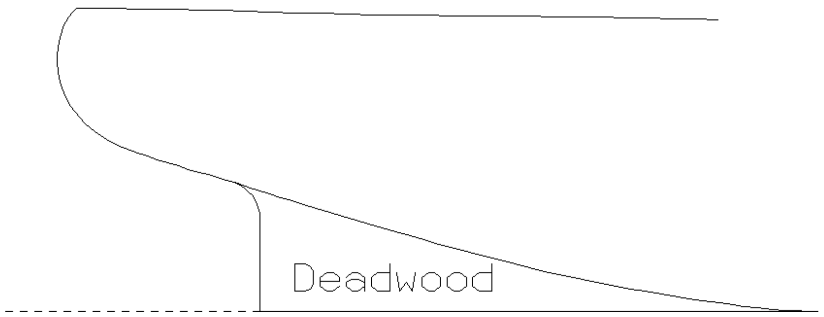


Figure 2-10: Deadwood at aft end of ship.

Depth, moulded of a ship hull (*D*) [L] —The moulded depth of a ship, defined as the height above the baseplane of the lowest point of a deck where it joins the side of ship.
Diagonal —The trace on the outside of a body marking the intersection of a plane passing through it at an angle other than 90° to the baseplane. Specifically, for a ship of normal form, the diagonal plane is generally parallel to the baseline.

Dihedral, Angle (-) [-]—The complement of the acute angle between the plane of symmetry of a craft or body and the axis of a hydrofoil attached to it projected on to a transverse plane.

Dimensionless characteristic length (U) — R. E. Froude's dimensionless characteristic length $U = \nabla^{1/3}$ =cube root of the volumetric displacement

Displacement Mass (Δ_{m}) [M] **—**The mass of the water that a body displaces while floating.

Displacement Volume, molded (∇) [L^3] **—**The volume of water displaced by the molded submerged volume of the bare hull, plus all submerged positive or negative appendages.

Displacement Volume, total (∇) [L^3] **—**The volume of water displaced by the outside of the shell plating submerged volume of the bare hull, plus all submerged positive or negative appendages.

Drag (-) [L] **—**A designed trim. (American usage – See: *Trim*)

Draught (T) [L] —The vertical distance, from the water surface to the bottom, of the underwater body of a ship. Specifically, the draught moulded, at midships to the designed waterplane. When different, the draught at the transverse section having maximum area is indicated as T_{X}.

Entrance —See: *Body*.

Even Keel —This term is used to define the condition in which the ship has its keel parallel to the water surface. For vessels in which the keel is not straight or normally parallel to the water surface its use is not recommended: "zero trim" or "level trim" are preferred.

Fin —A fixed or moveable hydrofoil, attached to a ship generally in a longitudinal direction, to improve the dynamic stability or manoeuvrability, or to provide a lift force to windward, as in the fin keel of a sailing yacht.

Flap — A hinged, movable, auxiliary hydrofoil, forming the aftermost portion of a main hydrofoil.

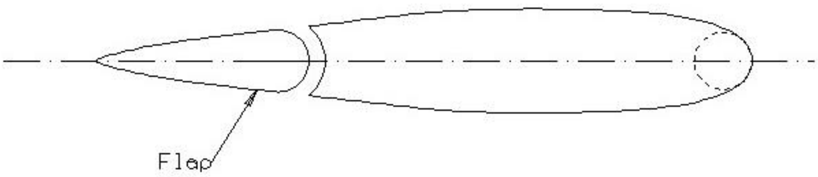


Figure 2-11: Hydrofoil with flap

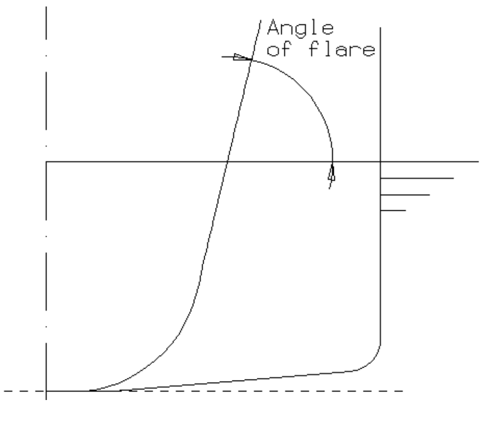


Figure 2-12 Transverse ship section with flare.

Flare — The slant upward and outward from the vertical of a transverse section of a hull above the design waterline. Flare is opposite of tumblehome; its slope measured with respect to the horizontal, generally in the entrance and generally less than 90°, is called Angle of flare.

Floor, rise of - or deadrise (-) [L] —The vertical distance above the baseline of the intersection point of the prolongation of the flat of the bottom at the maximum section area with a vertical straight line at half-beam from the centreplane.

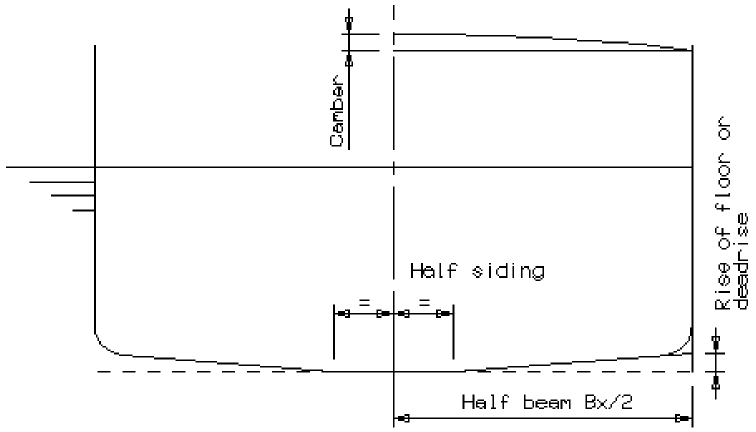


Figure 2-13: Geometrical characteristics of midship section.

Forefoot —The part of the bow of a ship at or near the intersection of the stem with the keel.

Frame section —The intersection of the hull form with a vertical transverse plane, at the position of a transverse frame of the ship.

Freeboard (*f*) [-]—The vertical distance between the surfaces of the undisturbed water, in which a ship is floating, and the edge of a reference deck (Freeboard deck) or other reference point. In certain governmental load line rules, a minimum freeboard is specified at midship.

Girth (-) [L] —The distance around the perimeter of any transverse station, section, or frame, between two selected points. For wetted surface calculations, these two points are generally the waterplane intersections.

Half-siding (-) [L] —The half breadth, at any section, of the portion of the bottom, in the vicinity of the keel that is perpendicular to the centerplane, i.e. parallel to the baseline.

Hull —The body of a ship, including the above water and the underwater portions. It is used to express either its form or its structure.

Hull, naked —The condition of a ship or model in which the fair form and the surface are represented without appendages or additions of any kind; it is also called bare hull.

Hydrofoil, span (*b*) [L] —The length of a hydrofoil from tip to tip, from root to tip if cantilevered, or from end support to end support, measured normal to the direction of relative liquid motion.

Keel —The term is used, alone or characterised with an appropriate adjective, to indicate:

i. The intersection of the plane of symmetry with the moulded hull surface at the bottom which is called the “keel line”. It may be parallel to the designed waterline or may be raked or sloped in the fore and aft direction (see Figure 2-2).

ii. The keel as the central longitudinal girder. This may be of the flat type (Flat keel) or a heavy bar extending beyond the fair form of the bottom (Bar keel –Appendages to improve the directional stability or reduce rolling: Bilge keel, an appendage, generally in the form of one or more long narrow fins, fitted along the side of a ship at the turn of the bilge to reduce rolling (See Figure 2-14).

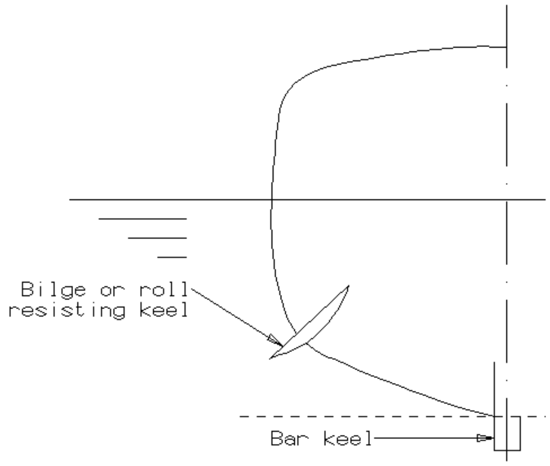


Figure 2-14: Bilge and bar keels.

Keel, fin —A deep, relatively thin, generally fixed plate or hydrofoil, attached to the underside of a ship (generally a sailing ship), to reduce the leeway and improve the directional stability. This fin keel can be on, or parallel to, the longitudinal centreplane.

Knuckle —See: *Chine*.

Leeward side of a ship — The side of a ship opposite to that the wind blows. It is opposite to the windward side.

Length (L) [L] (See Figure 2-15) —The principal longitudinal dimension of a ship or body; specifically for a ship it can be defined in a number of ways as follows:

Length overall (L_{OA}) [L]

Length overall submerged (L_{OS}) [L]

Length between perpendiculars (L_{PP}) [L]

Length on waterline (L_{WL}) [L] —When not defined, the length between perpendiculars is generally assumed. See also *Amidships* for ⌧ and *Perpendiculars* for AP and FP.

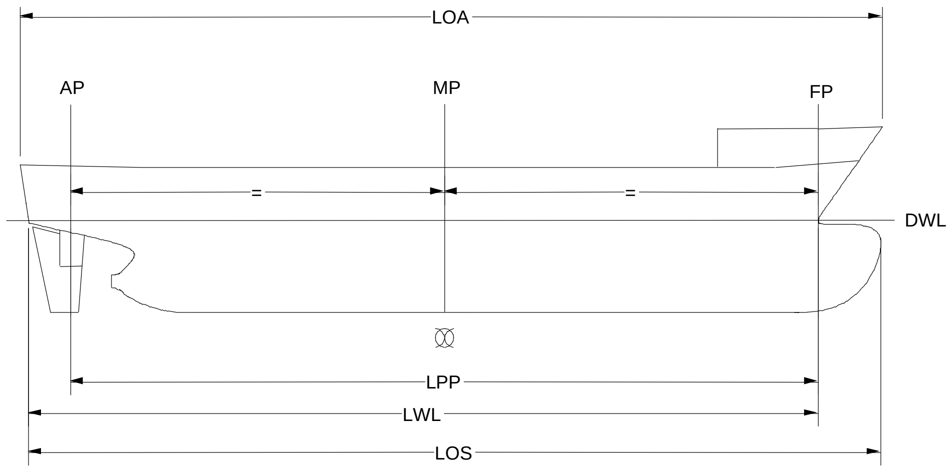


Figure 2-15 Characteristic ship lengths.

For a planing hull the following definitions of length are used: (See Figure 2-16**)**

Length, chine wetted under way of planing craft (L_C) [L]: —the length of the wetted part of the chine.

Length, keel wetted under way of planning craft (L_K) [L]: — the length of the wetted part of the keel.

Length, mean wetted, of planning craft (L_M) [L]: —the mean length of the portion of the bottom of a planning craft actually wetted when under way.

$$\boldsymbol{L_M = \frac{L_C + L_K}{2}}$$

Length, projected chine (L_{PR}): —Length of chine projected in a plane containing the keel and normal to longitudinal centre plane (See also Figure 2-3 and Figure 2-17).

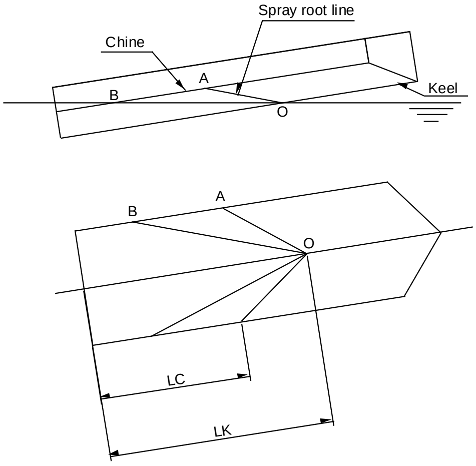


Figure 2-16: Characteristic lengths for a planning hull under way.

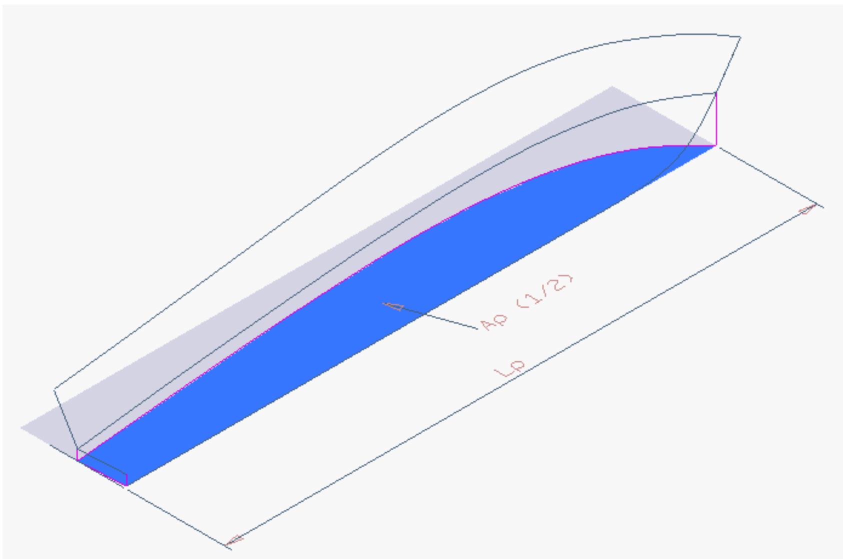


Figure 2-17: Planning bottom area.

Length coefficient of Froude, or length – displacement ratio (M^C) —The ratio of the ship length to the cube root of the volume of displacement:

$$M^C = \frac{L}{\nabla^{\frac{1}{3}}}$$

in a consistent system of units.

Lines —A drawing, depicting the form of a ship to the moulded shape and dimensions, showing the stations (transverse section or frames) waterlines, bowlines, buttocks and profile. (This includes a *Body Plan* which see.)

Maierform —A commercial name applied to a certain type of hull form with pronounced V sections at the fore end.

Mass Characteristics— Quantitative description of the mass and mass distributions of the ship (i.e., mass and mass distributions that establish the ship's lateral and transverse centers of mass and mass moments of inertia).

Maximum transverse section coefficient —See: *Sectional area coefficient*.

Metacentre, transverse (M) **and longitudinal** (M_{L}) [-]—The intersection of the vertical through the centre of buoyancy of an inclined body or ship with the upright vertical when the angle of inclination approaches to zero as limit, for transverse or longitudinal inclinations respectively.

Metacentre, transverse and longitudinal; height above the baseline, $\overline{KM}$ and ($\overline{KM_L}$) respectively [L]. —The height, measured vertically, of the transverse or longitudinal metacentre above the baseplane of a ship in the upright position.

Metacentre height, transverse ($\overline{GM}$) and longitudinal ($\overline{GM_L}$) [L]. —The distance between the centre of gravity and the transverse or longitudinal metacentre, measured vertically in the equilibrium position. It is positive when M is above G when the ship is said to have metacentric stability; that is, on inclination to a small angle a restoring moment arises which acts to return the ship to the vertical.

Metacentric radius, transverse ($\overline{BM}$) and longitudinal ($\overline{BM_L}$) [L]. —The height, measured vertically, of the transverse or longitudinal metacentre above the centre of buoyancy of a ship in the upright position. Geometrically, $\overline{BM}$ is the radius of curvature of the locus of the centre of buoyancy related to transverse inclinations, and $\overline{BM_L}$ the radius of curvature of the locus of the centre of buoyancy related to longitudinal inclinations. They are given by:

$$\overline{BM} = \frac{I_{\mathrm{T}}}{\nabla}$$

$$\overline{BM_L} = \frac{I_{\mathrm{L}}}{\nabla}$$

where:
I_{T} = transverse second moment of area (or moment of inertia) of the waterplane [L^4] (which see)
I_{L} = longitudinal second moment of area (or moment of inertia) of the waterplane [L^4] (which see)
∇ = volume of displacement [L^3]
(See Figure 2-18 for illustration of the transverse parameters.)

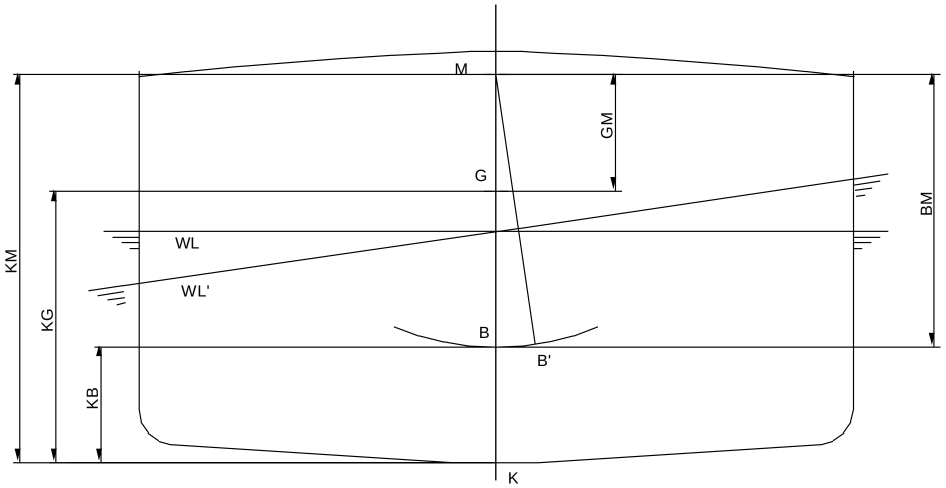


Figure 2-18 Transverse metacentric parameters.

Midship —See: *Perpendiculars*
Midship section coefficient —See: *Sectional coefficient.*
Midstation plane —See: *Planes, principal co-ordinate.*
Moment of area, second (or moment of inertia) [L^4] —The summation of the products of the elements of an area or surface squares and the squares of their distances from a given axis, generally in the surface. Especially for a ship:

Second moment of the waterplane area (or moment of inertia) longitudinal (I_L) — about the transverse axis through the centre of flotation.

Second moment of the waterplane area (or moment of inertia), transverse (I_T) —about the longitudinal axis through the centre of flotation, generally the intersection of the intersection of the waterplane and the centerplane.

Second moment of free-water surface (or moment of inertia) —generally within a ship, calculated about an axis passing through the centre of area of that surface, parallel to the expected heeling or rolling axis.

Moulded —An adjective used to indicate the generally fair form and dimensions of the hull as determined by the lines to the inside of the shell plating. For wooden ship it is taken to the outside of the planking.
Offset— One of a series of distances, measured from reference planes (normally from the centerplane), used for defining the size and the shape of a body or ship.
Overhang — Any portion of the abovewater hull of a ship which when projected downward on to the designed waterplane, lies outside that designed waterline; it may be at the bow or stern or anywhere along the side.
Perpendiculars (See Figure 2-15) —Straight lines perpendicular to the designed load waterline of a ship through a fixed point as stated by classification rules: specially:

Aft or after perpendicular (AP). — Through a fixed point at the stern; generally the aft side of the stern post, the centerline of the rudder stock in ship without a stern post or the intersection with the load waterline near the stern.

Fore or forward perpendicular (FP). —Through a fixed point at the bow; generally the intersection of the fore side of the stem with the load waterline.

Midship perpendicular or midship (MP, formerly ⊗)—Through the point in the middle of L_{PP}.

Planes, principal co-ordinate —The co-ordinate planes, formed by an orthogonal co-ordinate system of axes *x*, *y*, *z* fixed in the ship to define the hull shape (see *Axes, co-ordinate* in *General Section*):

Baseplane or *x-y* plane. — The horizontal plane, parallel to the designed waterline and generally through the lowest point of the midsection.

Centreplane or *x-z* plane. — The vertical longitudinal plane, which coincides with the plane of symmetry.

Plane, midstation, or *y-z* plane. — The vertical plane at midstation, perpendicular to the baseplane and the centreplane or plane of symmetry.

Plane of symmetry —See: *Planes, principal co-ordinate*.

Plane, transverse —Any vertical plane orthogonal to the baseplane of a ship.

Planform, projected —The contour of a ship, a hydrofoil, or appendage projected orthogonally on to a plane parallel to the baseplane.

Prismatic coefficient (C_P, formerly ϕ) [-]—The ratio of the volume of displacement to the volume of the cylinder having the length L and cross section of the maximum section of the ship. This sometimes called the longitudinal prismatic coefficient and is given by:

$$C_{\mathrm{P}} = \nabla/(LA_X)$$

The prismatic coefficient can also be referred to the different parts of ship, such as afterbody, forebody, entrance and run. In any case the assumed length, as well as the cross section area if different from the above, is to be clearly indicated.

Prismatic coefficient, vertical (C_{VP}, formerly ϕ_V) [-]—The ratio of the volume of displacement to the volume of a vertical cylinder having as horizontal section the waterline and as height the draught at midships. It given by:

$$C_{\mathrm{VP}} = \nabla/(TA_W)$$

When different, the draught of the transverse section having maximum area is used (T_X).

Profile —The outline of a ship when projected on to the centerplane; also the outline of parts of the ship, such as the stem, stern, and rudder, when similarity projected. For different shapes and types of stem and stern profile, see *Stem* and *Stern*. (See also *Manoeuvrability Section*)

Raked Keel —See: *Keel and Trim*.

Ram bulb or bow —See: *Bulb and Stem.*

Ratio, fineness, of a body —The ratio of the length *L* to the maximum diameter *D* of a body of revolution, or to the maximum breadth in other bodies.

Ratio, slenderness, of a ship (M_C) [-]—See: *Length coefficient of Froude*.

Run —See: *Body*

Scoop —An opening in the surface of the underwater body of a ship, which may or may not be fitted with a projection extending beyond that surface, designed for catching and taking water into a ship.

Section — Any transverse section perpendicular to the designed waterplane such as:

Area, maximum section the transverse section of the hull having the greatest immersed area to the design waterline. (A_X) [L^2]

Area, midship section, **midlength section**, **midsection** or **midstation** section (A_M) [L^2]

Section, ship shape —Any shape of transverse section considered typical in the development of ship forms. Some of this are:

Blister (See Figure 2-19a)), — in which an excrescence is added, near the waterline, to a more or less standard type of section.

Bulb (See Figure 2-19b)), in which there is a local swelling below the waterplane generally at bow or stern. (For details and variations see special entry *Bulb*)

Peg – top or battered (See Figure 2-19c)), in which there is a marked slope of the ship side outward and upward, generally but not necessarily above the designed waterline.

U-shaped (See Figure 2-19d)), rounded at the bottom and with sensibly straight, nearly vertical sides.

V-shaped (See Figure 2-19e)), relatively sharp at the bottom and with sensibly straight but flaring sides.

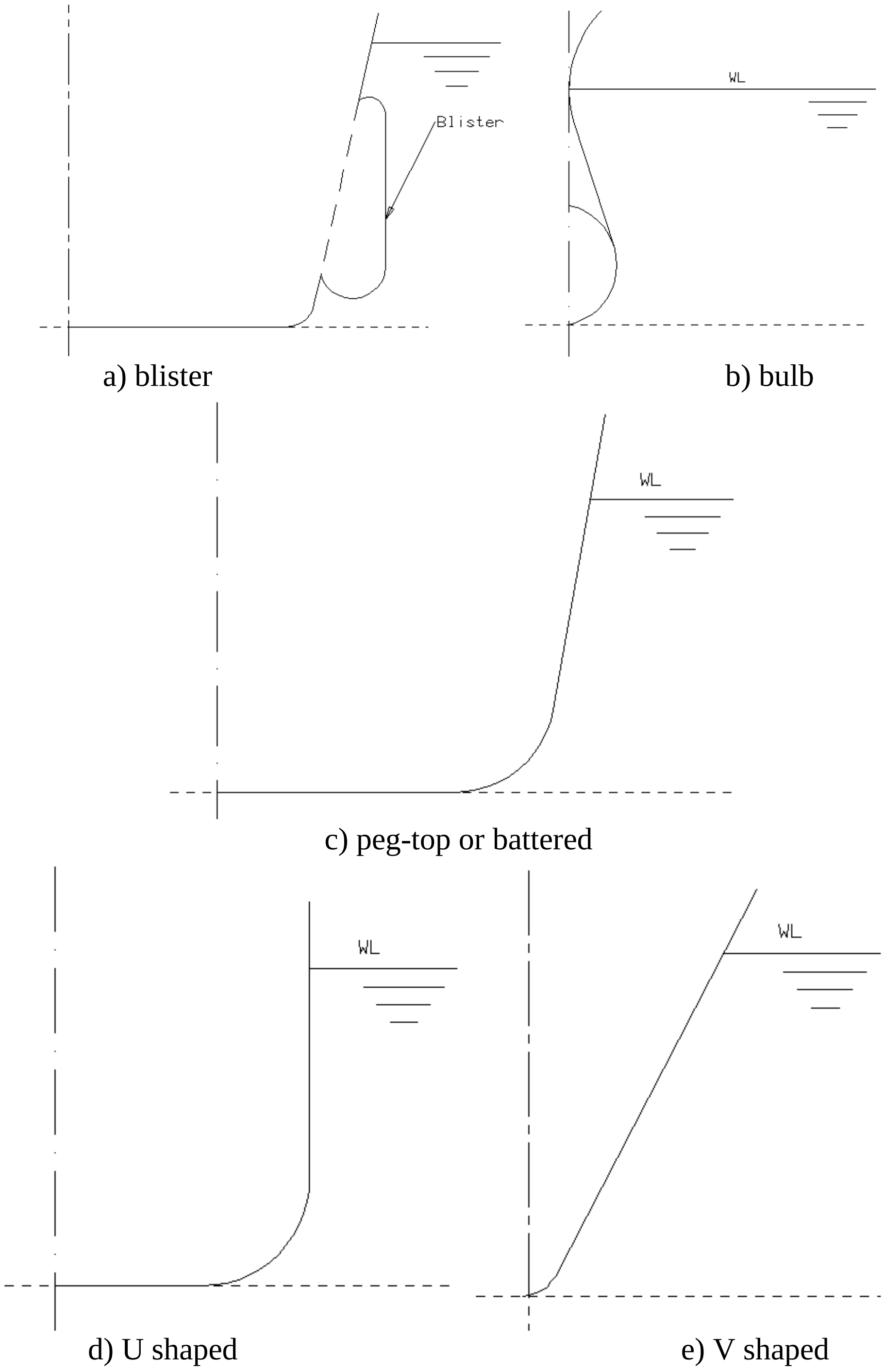


Figure 2-19 Typical shapes of transverse ship sections.

Sectional area coefficients (C_X), (C_M, formerly β) [-]—The *maximum transverse section coefficient*, C_X, is given by

$$C_X = {A_X}/{B_X T_X}$$

where A_X is the area of a maximum transverse section; B_X and T_X are the beam and draught at this section respectively.

The *midship section coefficient* C_M is given by

$$C_M = {A_M}/{B_M T_M}$$

where A_M is midship section area; B_M and T_M are the beam and draught at midship respectively.

Sectional area curve (See Figure 2-20) —A diagram of transverse section areas up to the designed waterline plotted on a base of length L, representing the distribution of underwater volume along the length of a ship; this diagram may be made dimensionless by plotting each ordinate as the ratio of area A of any section to the area A_X of the maximum section and by plotting the position of that section as a fraction of a ship length L along the base from selected reference points (generally forward and after perpendicular or midships). The intercept of the tangent to the sectional area curve at the bow on the midship ordinate expressed as a ratio of a midship ordinate is called the *Taylor tangent tot the area curve or midperpendicular intercept ratio or terminal value of Taylor "t"*. If the sectional area at the end ordinate is not zero (e.g. when there is a bulbous bow) both intercept should be diminished by that area in evaluating t. The midperpendicular intercept ratio was originally related to the tangent at the forward perpendicular only, but it can also be referred to the after perpendicular; therefore, the terms t_E and t_R may be used to indicate respectively the *midperpendicular intercept ratio for entrance* and the *midperpendicular intercept ratio for run* respectively.

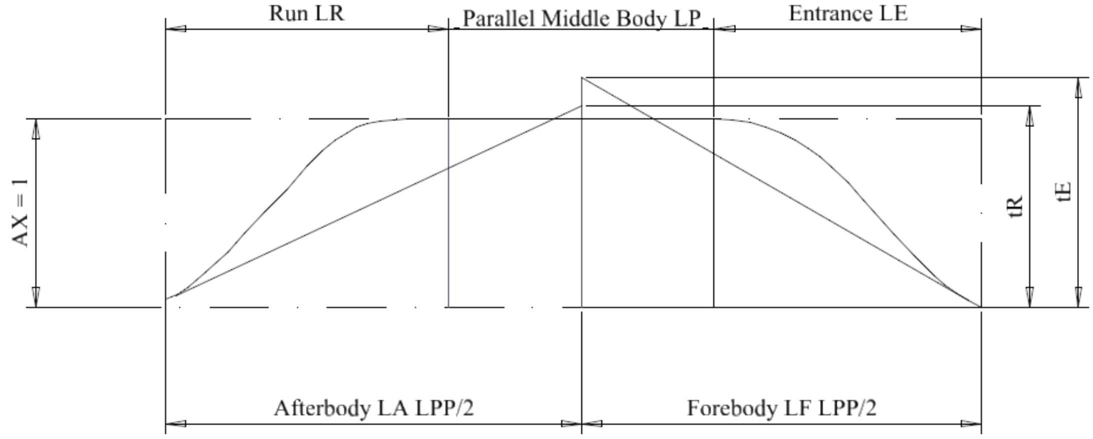


Figure 2-20: Characteristics of sectional area curve.

Shaft bracket or strut —See: *Strut* or *Shaft bracket*.

Sheer line —The projection on to the plane of symmetry of the intersection of deck with the side, or the intersection of a deck with the plane of symmetry of a ship when the deck has no camber (See Figure 2-21). The amount of rise of a sheer line above its lowest point is called the *Sheer*, forward or aft.

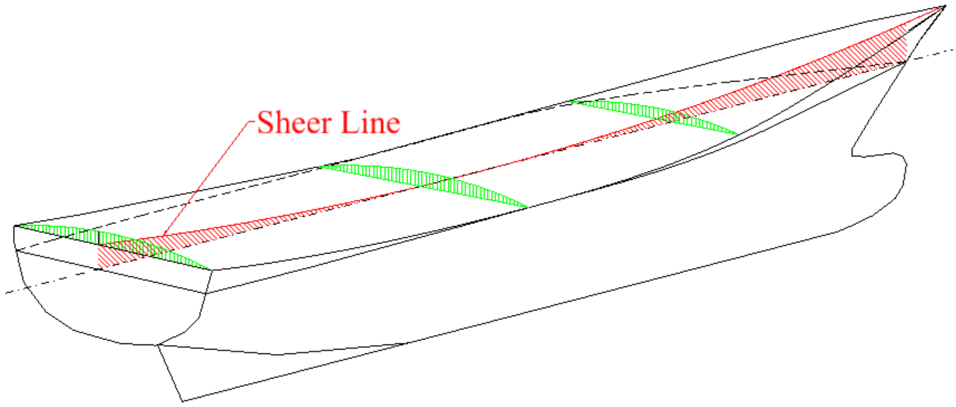


Figure 2-21: Definition of Sheer Line.

Shoulder —The portion of a ship, at the junction of the middle body with the entrance or the run, where the waterlines approach or reach their maximum width.

Skeg —The thin portion of the hull at the stern of a vessel immediately forward of or in the vicinity of the rudder. A skeg is usually of large lateral area compared to its transverse thickness, is provided for the support of a propeller shaft, for structural strength, for docking support, for protection when grounding or to increase the lateral area and give increased roll damping and course keeping ability to the hull or for other reasons. It is placed generally at the aft end, but not necessarily on the centreline. (See Figure 2-22).

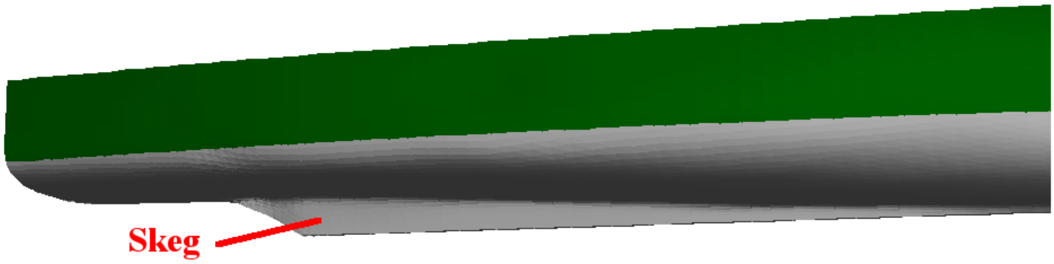


Figure 2-22: Example of hull with skeg.

Spray strip —A relatively narrow strip, of small cross-section, attached to the hull of a ship for the purpose of controlling or diverting spray.

Spread (-) [L] — The transverse horizontal distance between the centreplanes or the other designed plane or line of the two hulls of a catamaran or other multi-hulled craft.

Station —An imaginary transverse plane, passing through a ship, perpendicular to the baseline, to define the shape and the position of the various parts. Generally, the length between perpendiculars is divided by intermediate stations into 10 or 20 equal intervals. Specifically:

Maximum area station —the station at which the transverse section has the maximum area;

Midstation —the station at midlength**.**

Stem —The extreme forward end of a ship from the keel line to the top of the hull. Different names are given to various types and shapes and profile, such as:

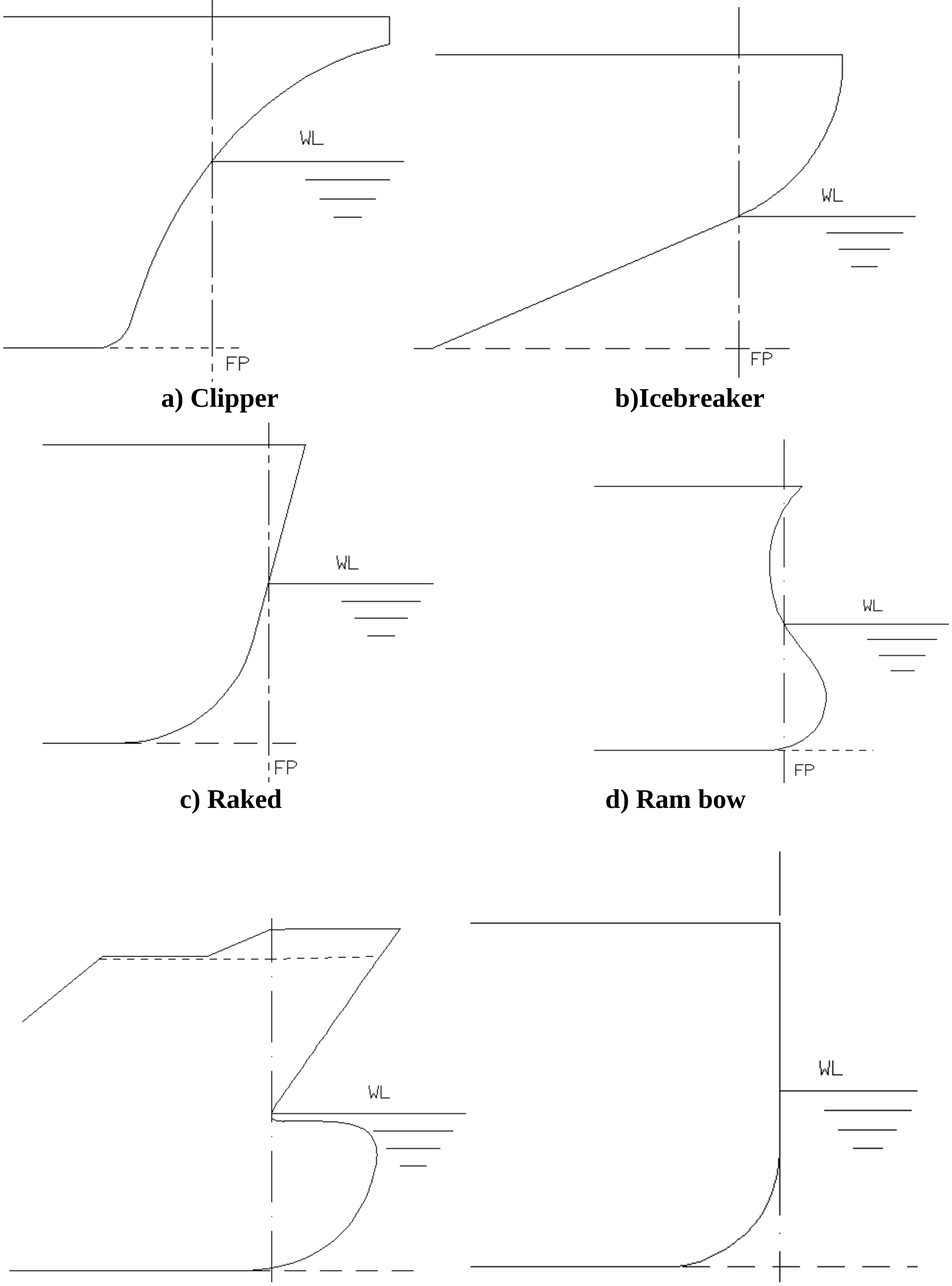
Clipper — in which the stem profile forms a concave curve which projects forward above the designed waterline, which a relatively large overhang. (See Figure 2-23a))

Icebreaker. — (See Figure 2-23b))

Raked — a straight profile inclined forward. (See Figure 2-23c)).

Ram — in which the underwater stem profile extends beyond the forward perpendicular.(See Figure 2-23 d), Figure 2-23e) and also *Bulb*)

Vertical (plumb) —, a straight profile coinciding with, or almost coinciding with, the forward perpendicular. (See Figure 2-23f))



a) Clipper b)Icebreaker c) Raked d) Ram bow e) Bulbous bow f) Vertical

Figure 2-23 Types of stem profile.

Step —The abrupt discontinuity in the profile of the bottom of a planning craft, designed to diminish resistance, to lessen the suction effects and to improve control of the longitudinal attitude. (See Figure 2-24)

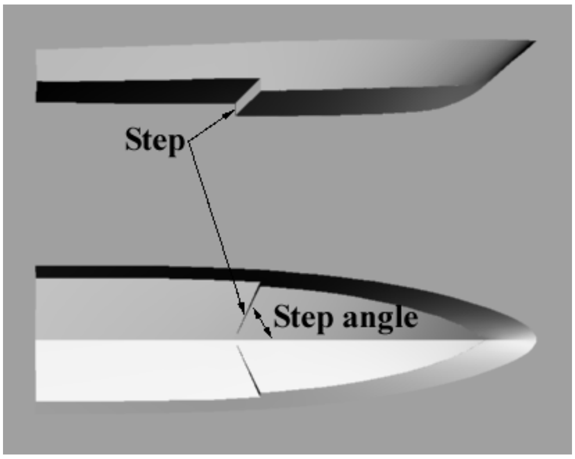


Figure 2-24: Step in planning craft hull.

Step angle —Angle projected upon the designed waterline, between the lower corner of a step or a planning craft and the centreline. (See Figure 2-24)

Stern —The extreme after end of a ship from the keel line to the top of the hull. Different names are given to various types and shapes of stern profile, such as:

Counter or fantail— in which the deck extends abaft the rudder post forming an elongated extension with appreciable overhang. With this type of stern the deck line is generally broad and full, but the waterlines are generally fine. (See Figure 2-25 a))

Cruiser —in which the stern profile as a convex shape, as indicated in Figure 2-25 b).

Transom— in which the buttocks and the waterlines, above and below the designed waterline, terminate abruptly in a transverse flat or convex surface or transom. The transom may be vertical or slightly raking aft. (See Figure 2-25 c))

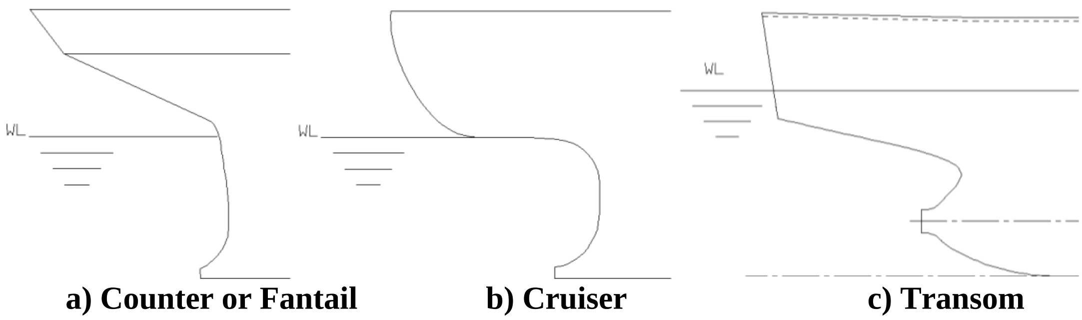


Figure 2-25 Types of stern profile.

Stern, contra type A curved non symmetrical form of stern, or skeg ending just a head of a screw propeller, designed to impart a rotation to the propeller inflow against the direction of rotation of a propeller.

Sternpost —A strong, rigid member forming the after end of the structure of some ships, and supporting the rudder.

Sternwheel —A paddlewheel mounted at the stern of a vessel which is called a stern-wheeler, as distinguished from a side wheeler.

Stock —The shaft or spindle upon which a rudder, diving plane, or equivalent control surface is mounted. The rudder or plane is generally, but not necessarily, turned by the stock.

Strut or shaft bracket (See Figure 2-26) —A bracket supporting the outboard end of a propeller shaft in twin or multiple–screw vessels having propeller shaft fitted off the centreplane. This is sometimes referred to as an “A” bracket. It usually consists of a barrel fitted with a bearing for the shaft, connected to the shell by one or two streamlined arms (*Strut arms*)

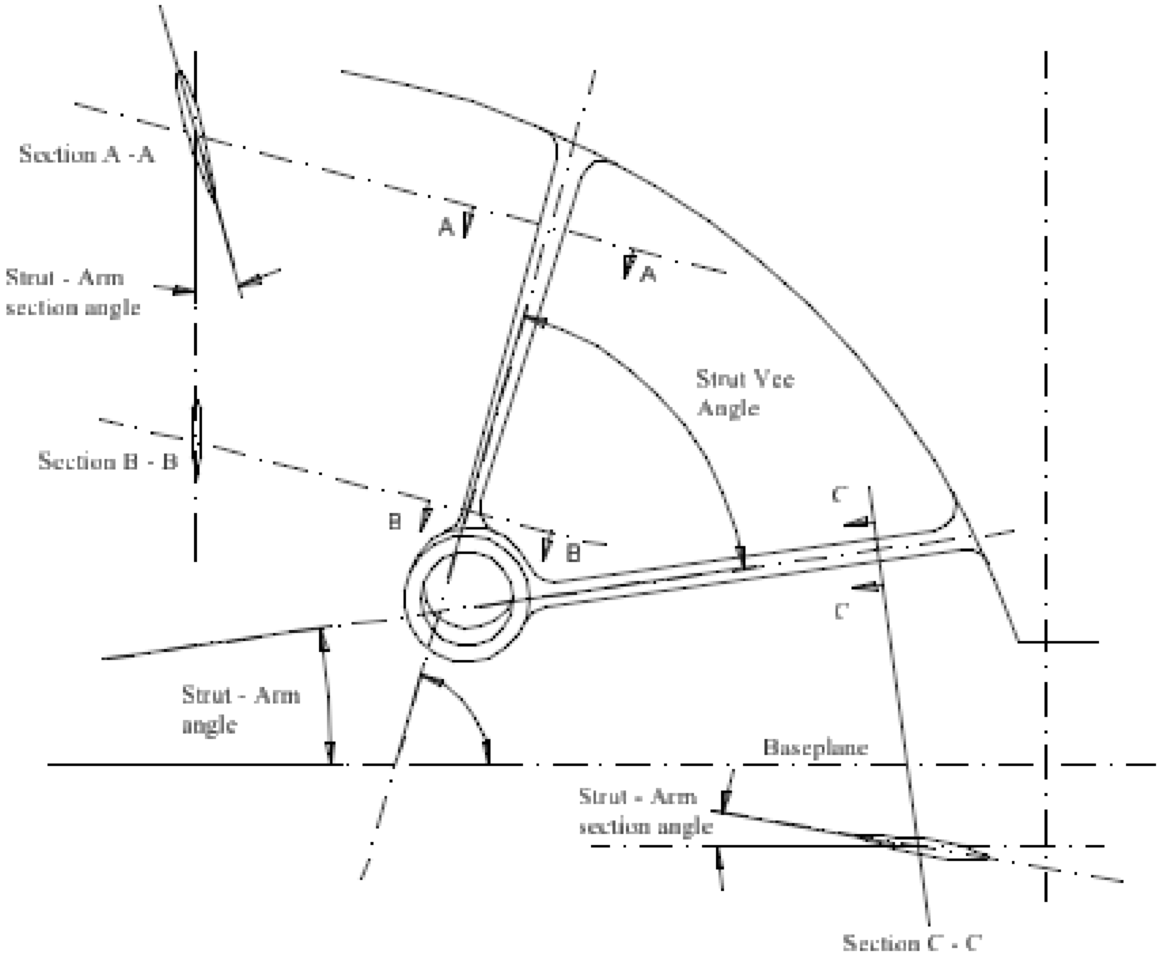


Figure 2-26 Characteristics of propeller strut or shaft bracket.

Strut–arm angle (See Figure 2-26 —The angle between the axis of any strut arm and the baseplane of a ship when projected on to a transverse plane.

Strut-arm section angle (See Figure 2-26) —The angle between the meanline of a strut arm section normal to its axis at any selected point along the arm and a line lying in the plane of that section parallel to the centreplane or baseplane.

Strut-vee angle (See Figure 2-26) —The angle between the axes of the two arms of a V-shaped strut, when projected on to a transverse plane.

Surface, wetted (*S*) [L^2] —The surface area of the underwater body of a ship. This generally includes the area of the appendages which give an appreciable contribution to the frictional drag, such as bilge keel, propeller bossing, and rudder. It is usually expressed in non dimensional form viz:

1) **Wetted surface coefficient** (C_S) [-] — $C_S = S/\sqrt{\nabla L}$ where: S = wetted surface area, L = ship length, and ∇ = volume of displacement or
2) **Froude's wetted surface coefficient** (S^C) [-] — $S^C = S/\nabla^{2/3}$

Tilt —An inclination of ship or its parts from the vertical or upright position, generally in a transverse or athwartship plane.

Transom —See: *Stern.*

Trim (-) [L] —The difference between the draught forward T_F and the draught aft T_A for a ship with a designed level keel: Trim = T_F - T_A

In non dimensional form the trim is expressed as a fraction of the ship length, i.e. $(T_F - T_A)/L$ and is called the trim ratio. It is referred to as trim by the bow or head if the forward draught is the greater, level trim if both are the same and trim by the stern if the draught aft is the greater. If the ship has a designed initial trim (raked keel or drag) the trim is generally measured with respect to this initial longitudinal inclination.

Tumblehome —The slant inward from the vertical of a transverse section of a hull above the designed waterline. It is the opposite of flare.

Turtleback or turtleback deck —A form of weather deck with large camber which is rounded over at the sides in order to shed the water rapidly in heavy weather; also called *turtle deck*.

Waterline —This term is used to indicate:

i. The intersection line of the free water surface with the moulded surface of a ship, either in still water or when it is surrounded by waves of its own making.
ii. The intersection line of any selected plane, parallel to the baseplane, with the moulded surface of a ship. (See Figure 2-27)

The angle of the waterline at the bow in the horizontal plane neglecting local shape at stern is the *Angle of entrance*. This is generally designated as the *Half angle of entrance* (i_E) [-] i.e. with respect to the centreplane - (See Figure 2-27).

The angle of the waterline at the stern in the horizontal plane neglecting local shape of stern frame is the *Angle of the run*. This is generally designated as *Half angle of run* (i_R) [-] i.e. with respect to the centreplane – (See Figure 2-27).

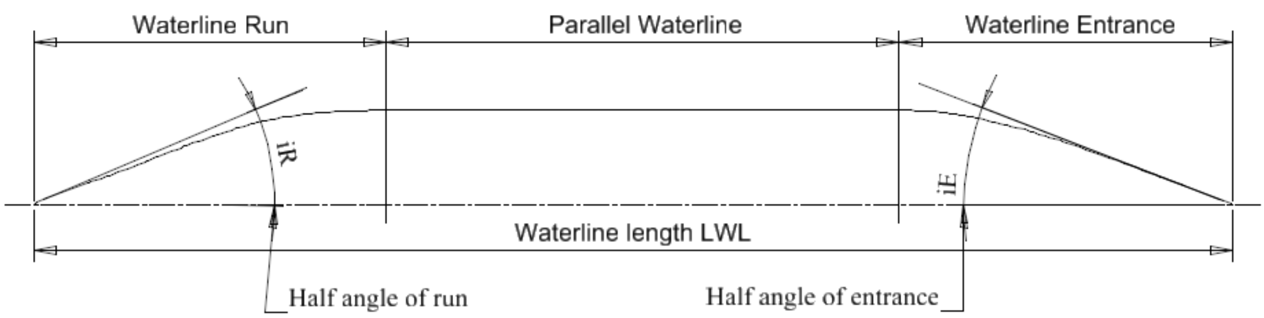


Figure 2-27: Waterline characteristics.

Waterplane —Any selected plane through a ship from and a parallel to the baseplane, specifically:

Designed Waterplane, —corresponding to the designed waterline.

Maximum waterplane, —corresponding to the waterline of a ship at the draught at which the waterplane area is maximum.

Waterplane area (A_W) [L^2] —The area enclosed by a waterline.

Waterplane area coefficient, designed load (C_{WP}, formerly α) [-]—

$$C_{WP} = A_W/LB_{WL}$$

where:
$L = L_{WL}$ = Length on the waterline
B_{WL} = maximum breadth of the waterline.
See Figure 2-28.

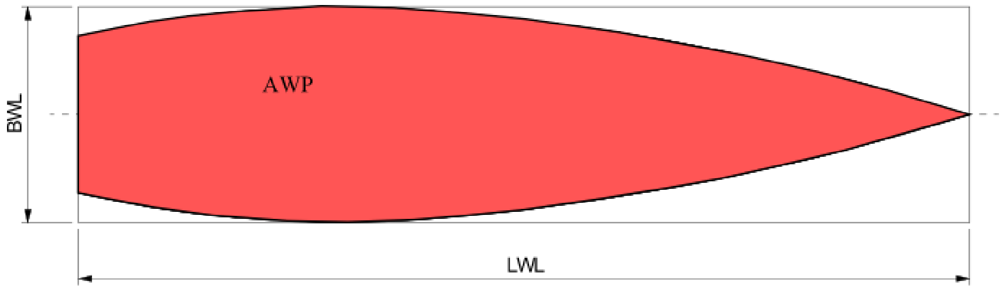


Figure 2-28: Waterplane area coefficient quantities.

Waterplane inertia coefficients—
Longitudinal $C_{IL} = 12\, I_L / BL^3$
Transverse $C_{IT} = 12\, I_T / B^3 L$
where:
I_L = longitudinal second moment of area (or moment of inertia) of the waterplane.
I_T =transverse second moment of area (or moment of inertia) of the waterplane.

Windward side — The side of a ship on which the wind blows. It is the opposite to the leeward side.

6. Dynamic stability (Including Other Section References)

Broaching—An involuntary and dangerous change in heading produced by a severe following or quartering sea. (See also the stability section)

Broaching (MCA) **—** is a severe, and often uncontrollable, yawing movement in following seas which turns the vessel beam on to the waves resulting in a dangerously heavy roll, and a sideways sliding motion down-sea. In monohulls with insufficient stability it can result in capsize. It maybe preceded by surfing.

Buoyant Volume—The watertight volume of a vessel

Note: USCG NVIC 5-86: — Deckhouses should be included in the buoyant volume only if:

a. They are of substantial construction so that they can withstand the impact forces of waves,

b. They have internal access to the spaces below; otherwise it should be assumed that the exterior doors will be used for access, thus disrupting the buoyant envelope watertight integrity.

c. All openings in the sides of the deckhouse are weathertight. (NOTE: Joiner doors should not be considered as weathertight.),

d. All windows have deadlight covers. In general, volumes which are watertight and of sufficient strength are fully effective. The Coast Guard recommends that all fully effective volumes be included in the buoyant volume for the righting arm calculations. Although the exclusion of these volumes may be more conservative, using the allowed buoyant volumes permits a more accurate assessment of the vessel's stability characteristics.

Capsize- —See **Stability**

Centers of Buoyancy, Flotation and Gravity: —See Ship Geometry Section

Derivatives, stability and control: —See Manoeuvering Section

Dimensionless characteristic length (U) — R. E. Froude's dimensionless characteristic length $U = \nabla^{1/3}$= cube root of the volumetric displacement

Displacement mass (Δ_M) — The mass of the water that a body displaces while floating.

Displacement volume (∇) —Displacement volume of the molded submerged volume of the bare hull, plus all submerged appendages

Downflooding (NSWCCD) — A consequence of an extreme motion that results in flooding. An example is where a large roll angle puts the intakes to the gas turbine into the water.

Downflooding angle (θf) (NSCV) — the smallest angle of heel at which downflooding will occur, if all weathertight closing appliances are properly secured (see NSCV Figure 3 and Figure 6). NOTE: The downflooding angle is often calculated assuming the centre of transverse flotation remains at the centre line of the vessel. This approximation tends to become less accurate at larger angles of heel. It is normally conservative on vessels that have considerable reserve buoyancy, but can overstate the downflooding angle on vessels that have minimal reserve buoyancy.

Dynamic stability—The characteristic of a body, such as an aircraft, rocket, or ship that causes it, when disturbed from an original state of steady motion in an upright position, to damp the oscillations set up by restoring moments and gradually return to its original state. *(McGraw Hill Dictionary of Scientific and Technical Terms*) **See Equilibrium and Stability**

Extreme Event:—An adverse ship motion and/or hydrodynamic loading event that, if it occurs, could cause loss of ship, loss of lives, crew injury and/or significant damage to the ship. Extreme Events include, but are not necessarily limited to, Capsize, Knock-down, Deck-diving, Broach, Slamming and Surf-ride.

Forces: exciting, damping, restoring: —See Seakeeping and Manoeuvring Sections.

Frequency: —See Seakeeping Section.

Green Water: — See Seakeeping Section.

Gyradius (radius of gyration): —See Seakeeping Section.

Heading: —See Seakeeping Section.

Heaving: —See Seakeeping Section.
Heel or list: — See Seakeeping Section.
Knock-down: —A large roll event in a seaway, defined at some point less than Capsize, that is unsafe and could lead to Down-flooding resulting in loss of ship, loss of lives and/or significant structural and/or equipment damage. An example is when the ship rolls to a large angle where the buoyancy effects of the superstructure are keeping the ship from an actual Capsize.
Long crested sea: —See Seakeeping Section.
Mass Characteristics: —See Ship Geometry Section.
Metacenter, transverse and longitudinal: —See Ship Geometry Section.
Metacentric height, transverse coefficient (C_{GM}) —The dimensionless distance between the center of gravity and the transverse or longitudinal metacenter, measured vertically in the equilibrium position. $C_{GM} = GM/\nabla^{1/3}$ i. e. GM/ cube root of the volumetric displacement
Moment of Inertia: —See Ship Geometry and Seakeeping Sections
Open vessel (NSCV) — a vessel that is not arranged to prevent the accumulation of larqe quantities of water on deck or in buoyant spaces if swamped. Such vessels—
1. are not provided with a deck that is effectively weathertight;
2. have a freeboard deck line that is in whole or part located below the deepest waterline; or have weather decks forming wells above the deepest waterline that are not arranged for rapid drainage of large quantities of accumulated water.

Parametric stability criteria —are expressed in simple mathematical form and are intended to reproduce the prescribed safety level associated with a dynamic mode of stability failure.
Pounding: —See Seakeeping Section
Resonance: —See Seakeeping Section
Righting arm coefficient (C_{GZ})—The dimensionless horizontal distance between the center of gravity and the vertical line of action through the center of buoyancy at any angle of heel. $C_{GZ} = GZ/\nabla^{1/3}$, the cube root of the volumetric displacement and R. E. Froude's characteristic length
Roll angle: —See Seakeeping or Maneuvering Sections
Sea direction: —See Seakeeping Section
Scenario analysis—is a process of analyzing possible future events by considering alternative possible outcomes (scenarios). The analysis is designed to allow improved decision-making by allowing more complete consideration of outcomes and their implications. For complex systems with unknown joint probabilities, useful scenarios can be classified into pessimistic, optimistic and likely scenarios.
Simplified stability criteria (NSCV)— a set of deemed-to-satisfy stability criteria that do not require the full analysis of stability using individual loading conditions to derive righting lever curves (*GFZ* curves). NOTES:
1. Simplified stability criteria are applied to enable the use of simplified test methods.
2. Simplified stability criteria are strictly limited in their application to avoid potential inaccuracies and erroneous conclusions as to a vessel's stability characteristics.

Simplified stability test methods (NSCV) — test methods that, if properly applied, can provide a simplified and normally less expensive approach to the determination of stability characteristics of certain specified types of vessels. NOTES:
1. Simplified test methods are not suitable where comprehensive intact stability criteria apply.
2. Simplified test methods may involve stability proof testing where measurements are taken of freeboards and angles of heel, or alternatively a practical inclining experiment for determining *GFMO*.

Slack tank— a tank that is neither completely empty nor full. For the purposes of this standard, a partially-fuilled tank that is less than 98% full is considered to be a slack tank.

Slamming (NSWCCD)—Ship motions that result in hull or appendage exposure above the sea and subsequent re-entry resulting in large hydrodynamic structural loading on the hull and appendages.
Spectrum: —See Seakeeping Section.
Stability, course: —See Manoeuvring Section.
Stability, directional: —See Manoeuvring Section.
Stability, dynamic: —See Manoeuvring Section.
Stability, straight-line: —See Manoeuvring Section.
Stability (ITTC)—The tendency of a ship to remain upright or the ability to return to her normal upright position when heeled by the action of waves, wind, etc.

Capsize (MCA): —When a vessel is heeled to any angle from which it cannot recover without assistance.

Capsize, Static *(NSSWC)* — A static capsize may occur suddenly when a disturbance is encountered that is sufficient to overcome the ship's inherent ability to remain in an equilibrium state at or near upright. The event has traditionally been characterized by parameters which relate to a reduction in the righting arm lever (or GZ curve) which represents the static stability of a vessel independent of forward speed and time. Conditions that could lead to static capsize include improper loading, lifting or topside icing (increasing VCG); towing, wind, or load shift,(increasing heel angle); trapped fluids on deck (increasing free surface effects); and loss of watertight integrity (loss of buoyancy/waterplane area).

Capsize, Dynamic *(NSSWC)*— A Dynamic Capsize is defined as a very large amplitude roll caused principally by seaway and wind excitation on a moving vessel or as a function of time. This wind and wave action may lead to equipment damage, personnel injury, loss of system functionality and/or weather-tight/watertight integrity due to which the ship is unable to maintain its intact upright state. A dynamic capsize is characterized as a time-dependent event occurring in unrestrained 6 degrees of freedom motion. The loss of dynamic stability may occur under a variety of conditions (intact or damaged) once the forcing function exceeds the available restoring force. The capsize mode is often one of 5 main phenomena:

1. Sympathetic Rolling — Generally occurs in stern or stern-quartering seas with greater risk when traveling at or near the wave group velocity. There are two general types of dynamic rolling characterized by their time to occur:

   Asymmetric resonant behavior: — When the roll behavior is asymmetric in nature and builds with each wave encounter. This is the generation of large amplitude oscillations in roll (as well as surge, sway and yaw motions) which occur as the result of fluctuations in the righting arm with the slow passage along the ship of long steep waves.
   Sudden extreme behavior—*:* This mode of capsize is generally due to a sudden loss of transverse waterplane area and righting ability when a wave crest is at or near amidships. Rolling motions coupled with the loss of transverse hydrostatic stability lead to capsize.

2. Resonant Excitation — This mode of capsize occurs in beam seas when a ship is excited at or close to its natural roll period.
3. Parametric Excitation — This mode of capsize is predominantly a following seas phenomenon, but it can also been observed in head seas at low forward speeds. It is the periodic variation of the righting arm and buoyancy distribution which results in a gradual build-up of excessively large roll angles at the same natural roll period as the vessel. These roll oscillations are most critical when the wave encounter frequency is approximately half that of the vessel's own natural roll period, though they may also occur at wave encounter frequencies

that are multiples of half of the vessel's natural roll period. The phrase "wave encounter frequency" is the common-usage term for what is technically the wave group encounter frequency.

4. Impact Excitation —This mode of capsize occurs when a steep or breaking wave impacts the ship and results in an extreme roll angle.
5. Large Amplitude Roll —This mode of capsize may be single or multiple rolls produced by other dynamic effects (e.g. broaching – following a large sudden yaw) in addition to wind and wave forces.

Note: Some of the above modes can occur sequentially or in combination, ultimately leading to capsize.

Extreme Event (NSWCCD) —An adverse ship motion and/or hydrodynamic loading event that, if it occurs, could cause loss of ship, loss of lives, crew injury and/or significant damage to the ship. Extreme Events include, but are not necessarily limited to, Capsize, Knock-down, Deck-diving, Broach, Slamming and Surf-ride.

Broaching — Broaching is a type of ship directional instability which is characterized by a sudden large yaw from the original heading. A broach can arise in following and stern-quartering seas and may manifest itself in a number of ways:

Broaching Caused by a Single Wave—Usually the result of one or a number of motions that includes surf riding or bow submergence and coupled pitch, roll and yaw instability at high speed. All are possible in following or stern-quartering seas.

Deck Diving— A condition where the ship buries its foredeck in a wave, often resulting in a rapid reduction in ship speed. This can result in structural damage to the superstructure and injury to personnel and can lead to capsize or pitchpoling

Knock-down— A large roll event in a seaway, defined at some point less than Capsize, that is unsafe and could lead to Down-flooding resulting in loss of ship, loss of lives and/or significant structural and/or equipment damage. An example is when the ship rolls to a large angle where the buoyancy effects of the superstructure are keeping the ship from an actual Capsize.

Low Frequency Large Amplitude Yaw Motions—This typically happens at higher ship speeds in moderate stern-quartering seas. A gradual build-up of oscillations in yaw occurs as successive waves impinge on the ship from behind. As the motion hits resonance, yaw amplitude increases until large amplitude yaw motions are displayed.

Successive Overtaking of Waves— This mode of broach occurs during the passage of several steep waves, gradually forcing the ship into beam seas. It occurs in steep following and quartering seas when the ship is travelling at a speed less than the mean wave group speed.

Surf Riding—Surf riding results from the ship moving down a wave crest with increasing speed. Large dynamic side forces may result if the ship imbeds itself in the proceeding wave. These dynamic forces may add to other dynamic forces to produce a dynamic capsize. Surf riding most frequently occurs when the ship is traveling near the wave speed.

Damaged Condition analysis —Includes dynamic stability considerations, subdivision, and free communication with the sea.

Dynamic Stability (IMO) —The resistance to stability failures in a seaway.

Impaired Static Stability*:*(DCM) — Conditions under which an intact hull suffers a reduction in its normal stability characteristics caused by (This needs work)

1. Addition of topside weight
2. Removal of low weight
3. Shifting of cargo
4. Other off center weight shifts and additions including free surface effects

5. Deterioration of reserve buoyancy (including water trapped on deck)
6. Flooding

Intact stability failure (IMO) —A state of inability of a ship to remain within design limits of roll (heel, list) angle and combination of lateral and vertical accelerations.

Partial stability failure (IMO) —An event that includes the occurrence of very large roll angles and/or excessive accelerations, which will not result in loss of the ship, but which would impair normal operation of the ship and could be dangerous to crew, passengers, cargo or ship equipment. Two subtypes of partial stability failure are intended to be included in the development:

1. roll angles exceeding a prescribed limit, and
2. combination of lateral and vertical accelerations exceeding prescribed limits

Total stability failure, or capsizing (IMO) **—**Results in total loss of a ship's operability with likely loss of lives. Capsizing could be formally defined as a transition from a nearly stable upright equilibrium that is considered safe, or from periodic motions near such equilibrium, passing through a far from equilibrium state that is intrinsically unsafe (or could be considered unacceptable from a practical point of view)

Static equilibrium stability: —The condition where the static heeling moment equals the static righting moment.

Watertight (NSCV) — a boundary that complies with the requirements for a watertight boundary in Part C Section 2. (Missing at present)

Wave: —See Seakeeping Section 6

Weather deck (NSCV) — **A** deck which is completely exposed to the weather from above and from at least two vertical boundaries to the space.

Weather tight (old NSCV) — **A** boundary such that, in any wind and wave conditions, water will not penetrate into the vessel.

Weather tight (new NSCV) — **A** boundary that complies with the requirements for a weather tight boundary in Part C Section 2. (missing at present) NOTE: A watertight boundary also meets the requirements of a weather tight boundary.

Well deck vessel (NSCV) — **A** vessel having an exposed recess, which extends for more than 50 per cent of the waterline length of the vessel (see NSCV Figure 2b)).

Wind angle, measured apparent — The direction of the measured relative wind with respect to a ship's heading. The uncorrected direction of the apparent wind induced by the ship's speed, motion at the anemometer and the true wind.

Wind angle, corrected apparent — The direction of the relative wind corrected for heel, roll, pitch, yaw, surge, sway and heave at the anemometer.

Wind angle, true — The direction of the true wind over the ground, with respect to a ship's heading.

Wind direction — The direction of any natural or atmospheric wind blowing over the ground or over the surface of the sea, measured from the true North.

Wind resistance — See: *Resistance wind*.

Wind velocity, measured relative — The velocity of the wind relative to the ship's heading. The uncorrected direction of the apparent wind induced by the ship's speed, motion at the anemometer and the true wind.

Wind velocity, corrected apparent — The velocity of the relative wind corrected for heel, roll, pitch, yaw, surge, sway and heave at the anemometer.

Wind velocity, true — The velocity of a natural wind relative to the ground.

Yaw, angle — The angle, measured about the vertical body axis, between the instantaneous position of the longitudinal centre plane of a ship when yawing (which see) and its mean heading. (Positive bow to starboard)

3. RESISTANCE

This section is concerned with fundamental aspects of the resistance of a ship, or body, to motion through calm water without consideration on the effects of the method of propulsion.

Angle of diverging waves — See: *Wave, angle of diverging.*

Blockage —The effects of the boundaries of channel or tunnel on the flow around a body

Blockage correction — A correction made to the results of a hydrodynamic experiments made in a channel or tunnel of one cross-section in order to estimate the equivalent results for another cross-section. Specifically, a correction made to the results of a resistance experiment in a towing tank in other to estimate the equivalent results in unrestricted water.

Boundary layer — The region of fluid close to a solid body where, due to viscosity, transverse gradient of velocity is large as compared with longitudinal variations, and shear stress is significant. The boundary layer may be laminar, turbulent, or transitional. See also *Flow, regime*.

Boundary layer thickness (δ, δ^* *or* δ_1 , θ, θ^* or δ^{**}) [L] — Definition depends on symbol.

Boundary layer thickness (δ_{995})—The distance normal to the surface of a body at which the speed attains that in an equivalent inviscid flow. For practical purposes this is sometimes taken as 99.5% of the inviscid flow speed or 99.5% of the total head.

Displacement thickness (δ^*, δ_1— the distance normal to the surface of a body by which streamlines outside the boundary layer are displaced. For two-dimensional flow:

$$\delta^* = \int_{y=0}^{\delta}\left(1-\frac{\bar{U}}{U_\delta}\right)dy$$

where U_δ = the velocity at the edge of the boundary layer and $\bar{U}$ = velocity in the boundary layer.

Momentum thickness (θ)— A parameter such that the quantity $\rho U_0^2\theta$ is the defect in the rate transport of momentum due to the boundary layer. For two-dimensional flow:

$$\theta = \int_{y=0}^{\delta}\frac{\bar{U}}{U_\delta}\left(1-\frac{\bar{U}}{U_\delta}\right)dy$$

Energy thickness (θ^*, δ^{**}):— A parameter such that quantity $\frac{1}{2}\rho U_0^3\theta$ is the defect in the rate of transport of kinetic energy due to the boundary layer. This is given by:

$$\theta^* = \int_{y=0}^{\delta}\frac{\bar{U}}{U_\delta}\left(1-\frac{\overline{U^2}}{{U_\delta}^2}\right)dy$$

Doublet —A source-sink pair where the axial spacing tends to zero as the product of axial spacing and the source strength remains constant. The value of that product is the “moment” of the doublet, and the direction from the sink to the source is the “axis” of the doublet. Consequently, a doublet of moment M (dimension L^4T^{-1}) and of axis x located in a point A generates at any point P a velocity potential:

$$\phi = -\frac{M}{4\pi r^2}\frac{\partial r}{\partial x} = -\frac{M}{4\pi r^2}\cos\theta$$

Where r = AP and θ = angle between AP and axis x_i. If M< 0, the axis of the doublet would be in the negative x-direction. In two dimensional problems, the definition holds. But the potential generated by a doublet of moment M (dimension L^3T^{-1}) and of axis x is:

$$\phi = -\frac{M}{2\pi r}\frac{\partial r}{\partial x} = -\frac{M}{2\pi r}\cos\theta$$

where r = AP and θ = angle between AP and axis x_i.

Drag (D) [LMT^{-2}] —The fluid force acting on a moving body in such a way as to oppose its motion; the component of the fluid forces parallel to the axis of motion of a body. Drag is the preferred term in aerodynamics and for submerged hydrodynamic bodies, while resistance is generally used in ship hydrodynamics. The various forms of drag are defined in relation to resistance. See also *Resistance*.

Drag coefficient (C_D) [-]—The non-dimensional ratio of the drag per unit of a representative area of a body to the dynamic pressure far ahead of the body.

Dynamic pressure —See *Pressure, dynamic.*

Equipotential line —A line in a potential flow field along which the velocity potential ϕ is constant.

Flow, laminar —The flow of a viscous liquid in which layers of laminae of fluid appear to slide smoothly past each other. Momentum transfer and shear between neighbouring layers of fluid are due to molecular interactions only.

Flow, potential —A flow field in which the fluid velocity $\overline{U}$ is equal to the gradient of a scalar velocity potential ϕ, $\overline{U}$ = grad ϕ, i.e. in which no vorticity is present, curl $\overline{U}$ = 0. See also *Potential function.*

Flow, regime —A term referring to the state of the flow in any region; the principal recognised regimes are laminar, transitional, turbulent and separated flows.

Flow, reversed —Flow occurring in an eddy or separated zone in which the local flow has a component opposite in direction to that of the main flow.

Flow, secondary —A transverse flow induced by the boundary layer geometry and by pressure conditions existing in the main flow.

Flow, separated —The detachment of the main fluid flow from a solid surface due to an adverse longitudinal pressure gradient sometimes caused by a sudden change of the direction or the curvature of the surface. The fluid in the separated flow contains eddies, and may be nearly static or may contain a region of reversed flow.

Flow, steady —Flow in which the velocity pattern is independent of time.

Flow, transitional —An unstable state of viscous flow between the laminar and turbulent regimes.

Flow, turbulent —A flow in which there are rapid and apparently random fluctuations both in the magnitude and in the direction of velocity. The velocity fluctuations may also be described by a random spectrum of vortices of varying size and strength. Turbulent resistance is higher than that in laminar flow at the same Reynolds number, because of the high momentum exchange by transverse fluctuations.

Flow, uniform —Flow in which all velocity vectors are parallel and equal.

Flow, viscous —The flow of a fluid where the flow characteristics include the effects of the shear forces acting on the fluid, and within it.

Fluid, perfect or ideal —A hypothetical fluid, which is homogeneous, inviscid and incompressible.

Frictional resistance —See: *Resistance*

Froude number (Fr) [-]—A dimensionless parameter expressing the conditions of dynamical similarity for flow systems influenced by gravity and inertia alone. In particular, it defines the speed at which geometrically similar models and ship will develop wave systems which are geometrically similar. It is given by:

$$Fr = \frac{V}{\sqrt{gL}}$$

The length term L is usually the length of the ship. Other forms of the Froude number use some other characteristic dimension, such as the cube root of volume of displacement, the submergence depth or the depth of water in restricted waterways.

Head (h) [L] —The height of a given fluid which the pressure in question would support.

Irrotational flow —See *Flow, potential*.

Laminar sublayer —See *Sublayer, laminar*.

Line, equipotential —See *Equipotential line*.

Number, Froude —See *Froude number*.

Number, Reynolds —See *Reynolds number*.

Potential flow —See *Flow, potential*.

Potential function or Velocity potential (ϕ) [L^2 T^{-1}] —In irrotational motion of a fluid, the velocity at any point may be derived from a single function ϕ such that its derivative with respect to distance in any direction is equal to the velocity component in that direction. See also *Flow, potential*.

Pressure, dynamic (q) [$L^{-1}MT^{-2}$] —The pressure change corresponding to the reduction of the momentum of a fluid element to zero, $q = (1/2)\rho U^2$.

Pressure, stagnation [$L^{-1}MT^{-2}$] — The total pressure measured at a stagnation point.

Pressure, static (p) [$L^{-1}MT^{-2}$] —The static pressure, p, at a point in a stream flow is that which would be recorded by a pressure gauge advancing with the speed of the local fluid and thus static with respect to it.

Pressure, total —This is the sum of the static and dynamic pressures.

Resistance (R) [LMT^{-2}] —The fluid force acting on a moving body in such a way as to oppose its motion; the component of the fluid forces acting parallel to the axis of motion of a body. Resistance is the preferred term in ship hydrodynamics, while drag is generally used in aerodynamics and for submerged bodies. Total resistance is denoted by R_T and various (not mutually exclusive) components of resistance are defined below. See also *Drag*.

Resistance coefficient (C_F, C_R, C_S, C_T, C_V, C_W, etc.) [-] —The non dimensional ratio of any specific component of resistance per unit area, to the dynamic pressure far ahead of the body.

Resistance, frictional (R_F) [LMT^{-2}] —The component of resistance obtained by integrating the tangential stresses over the surface of a body, in the direction of motion.

Resistance, frictional specific (C_F) [-]—An alternative name for the coefficient of frictional resistance, in which the reference area is taken to be the wetted area under consideration.

Resistance, pressure (R_P) [LMT^{-2}] —The component of resistance obtained by integrating the normal stresses over the surface of a body in the direction of motion.

Resistance, residuary (R_R) [LMT^{-2}] —A quantity obtained by subtracting from the total resistance of a hull, a calculated friction resistance obtained by any specific formulation.

Resistance, spray (R_S) [LMT^{-2}] —The component of resistance associated with the expenditure of energy in generating spray.

Resistance, viscous (R_V) [LMT^{-2}] —The component of resistance associated with the expenditure of energy in viscous effects.

Resistance, viscous pressure (R_{PV}) [LMT^{-2}] T—he component of resistance obtained by integrating the components of the normal stresses due to viscosity and turbulence. This quantity cannot be directly measured except for a fully submerged body when it is equal to the pressure resistance R_P.

Resistance, wave pattern (R_{WP}) [LMT^{-2}] —A resistance component deduced from measurements of wave elevations remote from ship or model where it is assumed that the sub surface velocity field, and hence the momentum of the fluid, can be related to the wave pattern by means of linearised theory . The resistance so deduced does not include wavebreaking resistance.

Resistance, wavebreaking (R_{WB}) [LMT^{-2}] —A resistance component associated with the break down of the ship bow wave.

Resistance, wavemaking (R_W) [LMT^{-2}] —The component of resistance associated with the expenditure of energy in generating gravity waves.

Reynolds number (*Re*) [-]—A dimensionless parameter expressing the condition of dynamical similarity for flow systems influenced by viscosity and inertia alone. For equal values of Reynolds number and the same orientation to the flow, the specific resistance coefficients of all geometrically similar smooth surfaces are identical as long as the uninfluenced speed field are similar and the flow is influenced by viscosity and inertia alone.
It is given by:

$$Re = \frac{VL\rho}{\mu} = \frac{VL}{\nu}$$

The length term L is usually the length of the surface, but the distance from the leading edge of the surface to a specific point, the diameter of a body, or the thickness of the boundary layer are sometimes used as length terms.

Separation —See *Flow, separated.*

Shear stress (τ) [$L^{-1}MT^{-2}$] —In a viscous fluid, the shear stress is the tangential resisting force per unit area acting on any boundary within the fluid. The specific value of the shear stress at a wall is denoted by τ_W.

Sink —A point at which fluid is assumed to be withdrawn symmetrically from all directions. The velocity potential due to a sink has the same form as the potential due to a source, but the strength Q is negative. See also *Source*.

Source —A point from which fluid is assumed to flow symmetrically in all directions. The strength Q of a source is defined in a three-dimensional flow as the volume of fluid issuing in unit time; its dimensions are L^3T^{-1}. (Some authors use $\sigma = Q/4\pi$ volume flow as source strength). A source at a point A generates at any point P a velocity potential:

$$\phi = -Q/(4\pi r)$$

where r = AP.
In a two dimensional flow parallel to a plane, a source at a point A is in fact a uniform distribution of sources on a straight line passing through A normal to the plane. The velocity potential due to such a source of strength Q is:

$$\phi = \frac{Q}{2\pi} \ln r$$

where r = AP and ln = natural logarithm.
Q is the volume of fluid issuing per unit time and per unit length in the direction normal to the plane. The dimension of Q is $L^2\ T^{-1}$. An irrotational flow of perfect fluid may be represented as due to distributions of source and sinks, or doublets, on some set of points.

Source, Kelvin —A Kelvin source is defined by the potential generated by a constant source in uniform rectilinear motion below the free surface of a perfect fluid.

Speed, hump (in high speed craft) [LT^{-1}] —The speed at which the resistance reaches a maximum before a planing craft enters the planing phase, or a hydrofoil craft enters the foilborne phase. (See Figure 3-1).

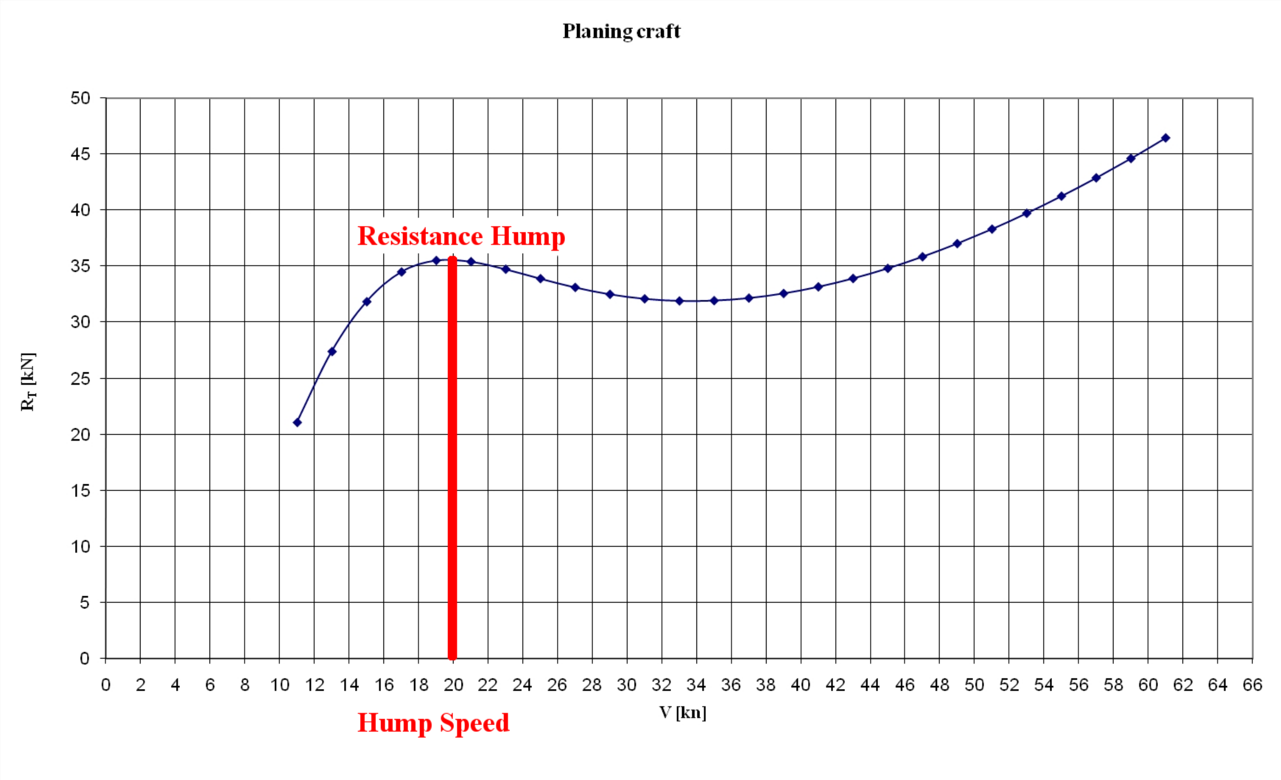


Figure 3-1: Resistance curve of a planing craft.

Stream-line —A line in a fluid such that its tangent at any point is parallel to the instantaneous velocity of the fluid at that point.

Sublayer, laminar —A very thin layer of laminar flow, within a turbulent boundary layer and adjacent to a solid surface.

Velocity potential —See *Potential function*.

Viscosity, coefficient of dynamic (μ) [$L^{-1}MT^{-1}$] —The quantity expressing the resistance of a fluid to internal shear; the ratio of tangential stress to rate of shear deformation in flow of an incompressible Newtonian fluid. For unidirectional shear flow:

$$\mu = \frac{\tau}{\mathrm{d}U/\mathrm{d}y}$$

Viscosity, coefficient of kinematic (ν) [$L^{-1}MT^{-1}$] —The ratio of the coefficient of dynamic viscosity to the mass density of the fluid:

$$\nu = \frac{\mu}{\rho}$$

See also General Section under "*Liquid Properties and Physical Constants*".

Wave, angle of diverging —The acute angle, measured in the horizontal plane, between axis of motion of a body and the normal to the crest or trough line.

4. PROPELLER

This section is concerned with propeller performance and various factor related thereto together with propeller geometry. Except where stated, the entries refer generally to screw propellers.

Active rudder —See: *Rudder, active.*
Advance angle (of propeller blade section) —See: *Angle, advance.*
Advance angle, effective —See: *Angle, effective advance.*
Advance coefficient (J) [-]—A parameter relating the speed of advance of propeller, V_A to the rate of rotation, n, given by $J = V_A/nD$, where D is the propeller diameter. The advance coefficient may also be defined in term of ship speed, V, in which case it is given by: $J_V = V/nD$.
Advance coefficient, Taylor's (δ)—A parameter defined as:

$$\delta = nD/V_\mathrm{A} = 101.27/J$$

where n is the rate of propeller rotation in revolution per minute, D is the propeller diameter in feet, and V_A is the speed of advance in knots.
Advance ratio (λ) [-]—A non-dimensional speed parameter relating the speed of advance, V_A and the rotational tip speed, πnD, given by:

$$\lambda = V_A/\pi nD = J/\pi$$

where J is the advance coefficient, D is propeller diameter and n its rate of rotation.
Advance, speed of —See: *Speed of advance*.
Analysis pitch —See: *Pitch, analysis*.

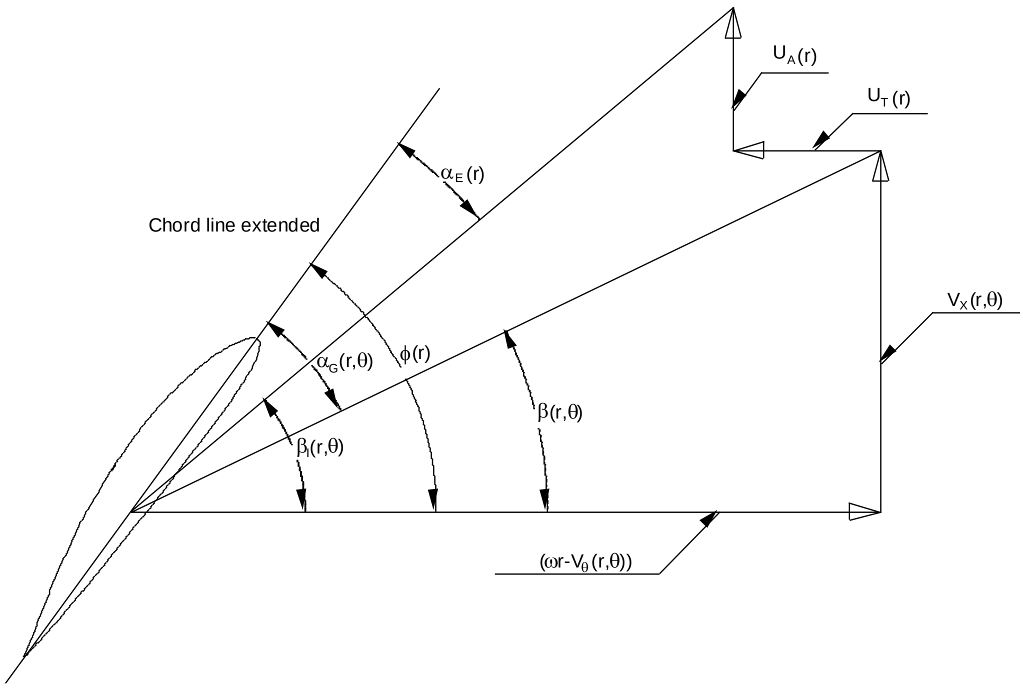


Figure 4-1: Typical velocity diagram for a propeller blade section at radius *r*.

Angle, advance (of a propeller blade section) (β) [-]—The inflow angle to a propeller blade section determined by the rotative speed, ωr, the axial velocity of the fluid, V_X, and the tangential velocity of the fluid V_θ, according to the equation:

$$\beta = \tan^{-1}\{V_X(r,\theta)/[\omega r - V_\theta(r,\theta)]\}$$

r is the radius of the blade section, ω the angular rate rotation and θ the angular position of the blade section. A simpler definition, also in use is:

$$\beta = \tan^{-1}(V_\mathrm{A}/\omega r)$$

where r is the radius corresponding to the section and V_A the advance speed.
The induced velocities are not included in the determination of the advance angle (See Figure 4-1).

Angle of attack (α) [-]—The angle measured in the plane containing the lift vector and the inflow velocity vector, between the velocity vector representing the relative motion between a body and a fluid and a characteristic line or plane of the body such as the chord line of an airfoil or hydrofoil. Synonymous with angle of incidence.

Angle of attack, effective (α_E) [-]—The angle of attack relative to the chord line including the induced velocities. See Figure 4-1.

Angle of attack, geometric (α_G) [-]—The angle of attack relative to the chord line of a section neglecting the induced velocities. See Figure 4-1.

Angle of attack, ideal (α_I) [-]—Angle of attack for thin airfoil or hydrofoil for which the streamlines are tangent to the mean line at the leading edge. This condition is usually referred to as a "shock free" entry or "smooth".

Angle, effective advance (β^*) [-]—A propeller inflow angle defined by the equation:

$$\beta^* = \tan^{-1}(V_\mathrm{A}/0.7\omega R)$$

where V_A is the speed of advance and r is the radius corresponding to the section.

Angle, hydrodynamic flow (β_I) [-]—The inflow angle to a propeller blade section including the axial and tangential induced velocities given by the equation:

$$\beta_\mathrm{I} = \tan^{-1}\left[\frac{V_X(r,\theta) + U_\mathrm{A}(r)}{\omega r - V_\theta(r,\theta) - U_\mathrm{T}(r)}\right]$$

U_A and U_T are induced axial and tangential velocities respectively (which see). For other items see *Angle, advance*. See also Figure 4-1.

Angle of incidence —Synonymous with Angle of attack.

Angle, shaft [-]—The angle or angles made by a shaft axis with the centre-plane and/or the baseplane of a ship. If a craft significantly changes attitude at speed, the shaft angle may, if so indicated, be measured between the shaft axis and the direction of motion.

Angle of zero lift (α_0) [-]—The angle of attack relative to the chord line for which the lift is zero.

Area, developed (A_D) [L^2] —An approximation to the surface area of the propeller equal to the area enclosed by an outline of a blade times the number blades. The outline of a blade is constructed by laying off, at each radius r, the chord length along an arc whose radius of curvature, r_1, is equal to the radius of curvature of the pitch helix given by $r_1 = r/cos^2 j$ where φ is the pitch angle at that radius. The outline is formed by the locus of the end points of the chord lines laid out in the above manner.

Area, disc (A_O) [L^2] —The area of the circle swept out by the tips of the blades of a propeller of diameter D:

$$A_O = {\pi D^2}/{4}$$

Area, expanded (A_E) [L^2] —An approximation to the surface area of the propeller equal to the area enclosed by an outline of a blade times the number of blades. The outline of a blade is constructed by laying off at each radius r, the chord length along a straight line. The outline is formed by the locus of the end points of the chord lines laid out in the above manner. (See Figure 4-2)

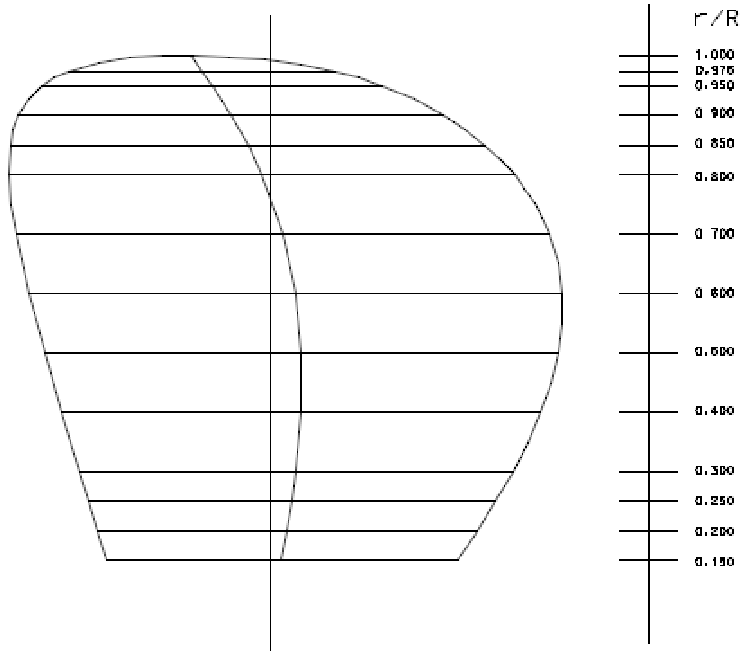


Figure 4-2: Expanded area of a propeller blade.

Area, projected (A_P) [L^2] —The area enclosed by the outline of the propeller blades outside the hub projected on to a plane normal to the shaft axis. The outline is constructed by laying off, along each radius r, the extremities of each section as determined in a view along the shaft axis. The locus of the end points of the chord lines laid out in the above manner is the required outline.

Axial induced velocity —See: *Induced velocity, axial*.

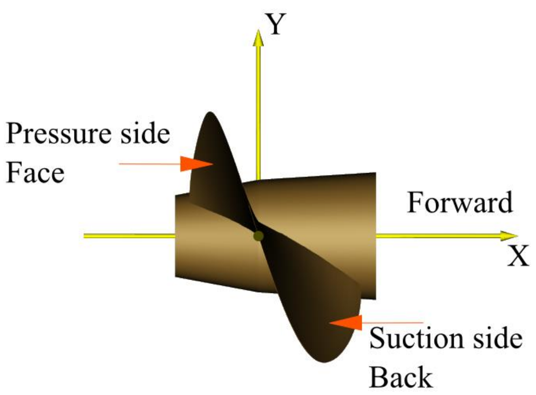


Figure 4-3: Propeller blade surfaces.

Back (of blade) The side of a propeller blade which faces generally in the direction of ahead motion. This side of the blade is also known as the suction side of the blade because the average pressure there is lower than the pressure on the face of the blade during normal ahead operation. This side of the blade corresponds to the upper surface of an airfoil or wing. (see Figure 4-3)

Blade —Element of a propeller, extending out radially from the hub. (see Figure 4-4).

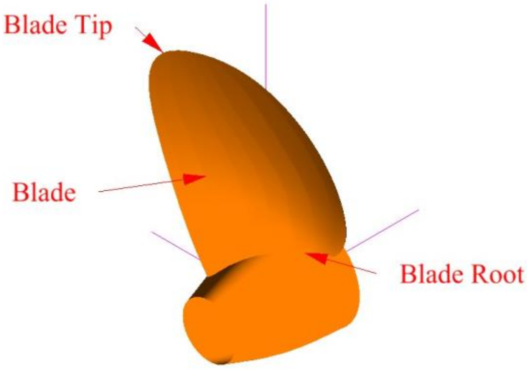


Figure 4-4: Propeller Blade.

Blade area ratio [-]—A term used to denote the ratio of either the developed or expanded area of the blades to the disc area. The terms expanded area ratio or developed area ratio are recommended in order to avoid ambiguity.

Blade outline —The line that marks the outer limits of the blade. (see Figure 4-5).

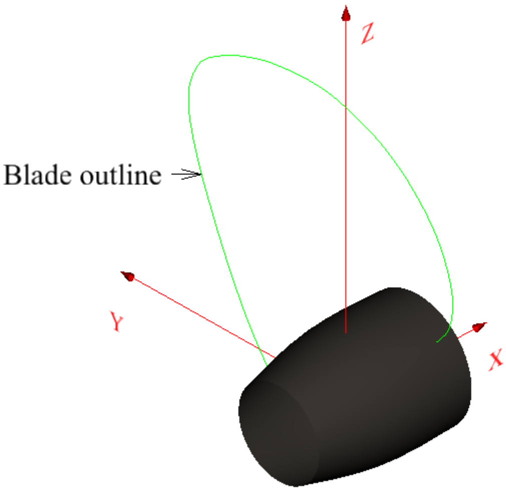


Figure 4-5: Propeller blade outline.

Blade root —Zone of transition from blade to hub. (see Figure 4-4).

Blade section —Most commonly taken to mean the shape of a propeller blade at any radius, when cut by a circular cylinder whose axis coincides with the shaft axis. (see Figure 4-6 and Figure 4-7).

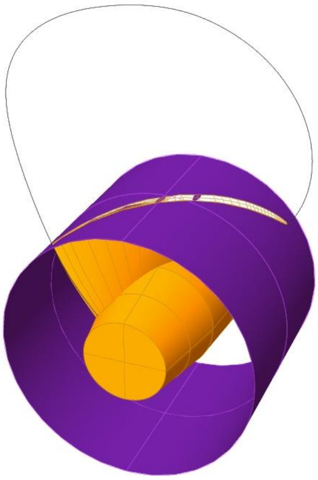


Figure 4-6: Propeller blade section

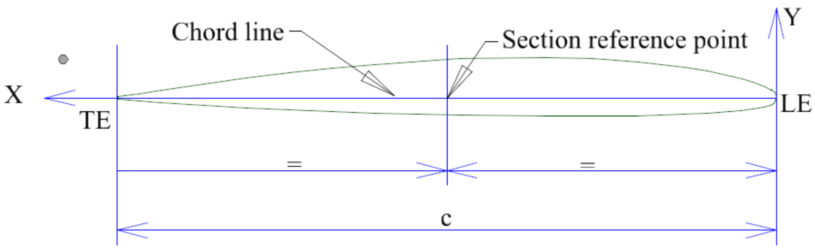


Figure 4-7: Unrolled generic propeller blade section.

Blade section reference point —See: *Reference point, blade section.*

Blade thickness fraction [-]—If the maximum thickness of the propeller blade varies linearly with radius, then this variation of thickness may be imagined to extend to the axis of rotation. The hypothetical thickness at the axis of rotation, t_0, divided by the diameter, is known as the blade thickness fraction or blade thickness ratio. If the thickness does not vary linearly with radius, then the blade thickness fraction is not uniquely defined.

Blade tip —Extreme part of the blade. (see Figure 4-4).

Bollard pull [MTL^{-2}] —The pull force exerted by a ship at zero ship speed. It is the sum of the propeller thrust and the interaction force on the hull.

Boss See: *Hub*.

Camber (f) [L] —The maximum separation of the mean line and the nose-tail line (see Figure 4-8).

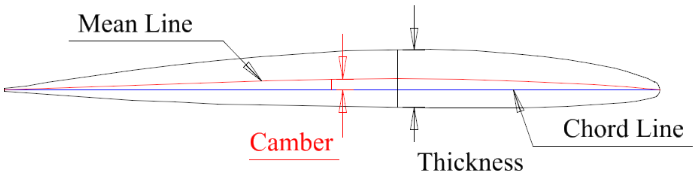


Figure 4-8: Blade section characteristics.

Camber ratio (δ_F) [-]—The camber divided by the chord length, f/c.

Cap, propeller —See: *Cone, propeller*.

Centrifugal spindle torque —See: *Spindle torque, centrifugal.*

Chord (c) [L] —The length of the chord line. Sometimes used synonymously with chord line (see Figure 4-7 and Figure 4-8).

Chord, leading part (c_{LE}) [L] —The part of the Chord delimited by the Leading Edge and the intersection between the Generator Line and the pitch helix at the considered radius (see Figure 4-9 and Figure 4-10).

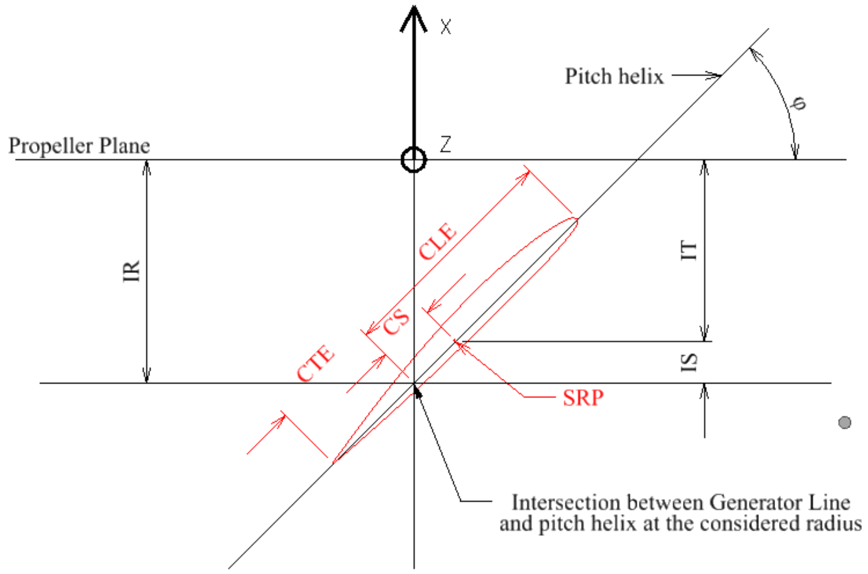


Figure 4-9: View of unrolled cylindrical section at radius r of a right-handed propeller (looking down) showing subdivisions of the Chord, Skewback and Rake.

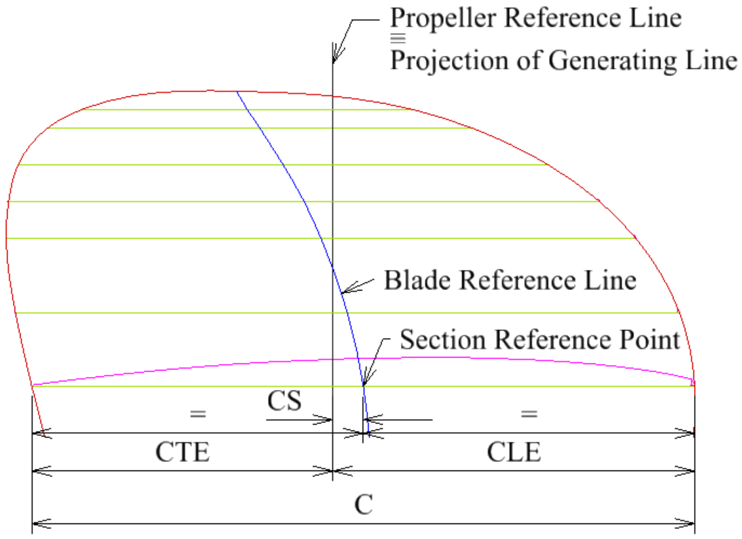


Figure 4-10: Portion of an expanded blade of a right-handed propeller, showing Chord subdivision.

Chord, trailing part (c_{TE}) [L] —The part of the Chord delimited by the Trailing Edge and the intersection between the Generator Line and the pitch helix at the considered radius (see Figure 4-9 and Figure 4-10).

Chord length, mean (c_M) [L] —The quotient obtained by dividing the expanded or developed area of a propeller blade by the span from the hub to the tip.

Chord line —The straight line connecting the extremities of the mean line. The length of this line is called the chord length or simply the chord. It passes through, or nearly through, the fore and aft extremities of the section. Synonymous with nose-tail line. (see Figure 4-7 and Figure 4-8)

Cone, propeller —The conical-shaped cover placed over the after end of the propeller shaft for the purpose of protecting the nut and forming a hydrodynamic fairing for the hub. Also known as a propeller fairwater or a propeller cap.

Contrarotating propeller —See: *Propeller Types*.

Cycloidal propeller —See: *Propeller Types*.

Developed area —See: *Area, developed*.

Developed area ratio (a_D)[-] —The ratio of the developed area of the propeller blades to the disc area.

Ducted propeller —See: *Propeller Types*.

Effective advance angle —See: *Angle, effective advance*.

Effective angle of attack —See: *Angle of attack, effective*.

Effective pitch —See: *Pitch, effective*.

Efficiency, mechanical (η_M) [-]—The ratio between the power output and the power input of any machinery installation.

$$\eta_{\mathrm{M}} = \frac{P_{\mathrm{S}}}{P_{\mathrm{I}}}$$

or

$$\eta_{\mathrm{M}} = \frac{P_{\mathrm{B}}}{P_{\mathrm{I}}}$$

where P_S and P_B are the shaft and brake powers respectively and P_I is the indicted power (which see).

Efficiency, propeller, behind hull (η_B) [-]—The ratio between the power P_T, developed by the thrust of the propeller and the power P_D absorbed by the propeller when operating behind a model or ship:

$$\eta_{\mathrm{B}} = \frac{P_{\mathrm{T}}}{P_{\mathrm{D}}} = \frac{TV_{\mathrm{A}}}{2\pi Qn} = \eta_0\eta_{\mathrm{R}}$$

where T is the thrust, V_A speed of advance, Q shaft torque and n rate of propeller rotation; η_0 and η_R are the open water propeller and relative rotative efficiencies respectively.

Efficiency, propeller, open water (η_0) [–] —The ratio between the power developed by the thrust of the propeller P_T and the power absorbed by the propeller P_D when operating in open water with uniform inflow velocity V_A:

$$\eta_0 = \frac{P_{\mathrm{T}}}{P_{\mathrm{D}}} = \frac{TV_{\mathrm{A}}}{2\pi Q_0 n}$$

T is the thrust, Q_O the torque in open water and n the rate of propeller rotation.

Efficiency, quasi-propulsive or quasi-propulsive coefficient (η_D) [-]—The ratio between the useful or effective power P_E and the power delivered to the propeller or the propulsion device P_D.

$$\eta_{\mathrm{D}} = \frac{P_{\mathrm{E}}}{P_{\mathrm{D}}} = \eta_0\eta_{\mathrm{H}}\eta_{\mathrm{R}}$$

where η_0, η_H and η_R are the open water propeller, hull and relative rotative efficiencies respectively (which see).

Efficiency, propulsive (η_P) [-]—The ratio between the useful or effective power P_E and the brake power P_B.

$$\eta_P = \frac{P_E}{P_B} = \eta_0 \eta_H \eta_R \eta_S \eta_G$$

where η_O, η_H η_R η_S and η_G are the open water propeller, hull relative rotative shafting and gearing efficiencies respectively (which see).

Efficiency, relative rotative (η_R) [-]—The relative rotative efficiency is the ratio of the propeller efficiencies behind the hull and in open water, as already defined.

$$\eta_R = \frac{\eta_B}{\eta_0}$$

Emergence, tip [L] —The vertical distance from the top of the propeller tip circle to the at-rest water surface when the tips are exposed.

Expanded area —See: *Area, expanded*.

Expanded area ratio (a_E) [-] —The ratio of the expanded area of the blades to the disc area.

Face (of blade) —The side of the propeller blade which face downstream during ahead motion. This side of the blade is also known as the pressure side because the average pressure on the face of the blade is higher than the average pressure on the back of the blade during normal operation. The face corresponds to the lower surface of an airfoil or wing. (see Figure 4-3)

Face pitch —See: *Pitch, face.*

Fillet —The transition region (fairing) between the propeller hub and the blades at the blade root.

Fully cavitating propeller —See: *Propeller types*.

Gap (G_Z) [L] —The distance between the chord lines of two adjacent propeller blade sections measured normal to the chord. This distance is given by the formula:

$$G_Z = (2\pi r \sin\varphi)/Z$$

where r is the radius in question, φ is the pitch angle of the chord line at the radius r (geometric pitch) and Z is the number of blades.

Generator line —The line formed by the intersection of the pitch helices and the plane containing the shaft axis and the propeller reference line. The distance from the propeller plane to the generator line in the direction of the shaft axis is called the rake. The generator line, the blade reference line, and the propeller reference line each intersect the shaft axis at the same point when extended thereto. Because of ambiguities which can arise in so extending the generator line and blade reference line when non-linear distribution of rake and skew angle are used, it is recommended that these lines be defined each to originate at the reference point of the root section (see Figure 4-21 and Figure 4-22). The rake and skew angle of the root section will thus be defined to be zero and the propeller plane will pass through the reference point of the root section.

Geometric angle of attack —See: *Angle of attack, geometric.*

Geometric pitch —See: *Pitch, geometric.*

Hub —The central portion of a screw propeller to which the blades are attached and through which the driving shaft is fitted. Also known as the boss.

Hub diameter (d_h) [L] —The diameter of the hub where it intersects the propeller reference line. (see Figure 4-11).

Hub diameter, fore (d_{hf}) [L] — Fore diameter of the hub, not considering any shoulder.

Hub diameter, aft (d_{hf}) [L] — Aft diameter of the hub, not considering any shoulder.

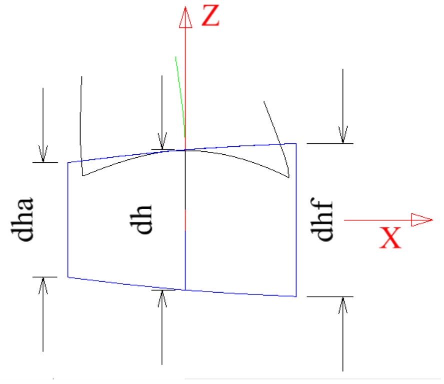


Figure 4-11: Hub diameters.

Hub length (l_h) [L] —The length of the hub, including any fore and aft shoulder (see Figure 4-12).
Hub length, aft (l_{ha}) [L] — Length of the hub taken from the propeller plane to the aft end of the hub including aft shoulder.
Hub diameter, fore (l_{hf}) [L] —Length of the hub taken from the propeller plane to the fore end of the hub including fore shoulder.

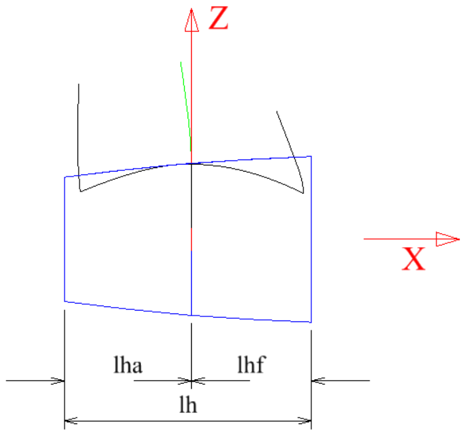


Figure 4-12: Hub length.

Hub ratio (x_B) [-]—The ratio of the diameter of the hub to the maximum diameter of the propeller, d_h /D.
Hydrodynamic flow angle —See: *Angle, hydrodynamic flow*.
Hydrodynamic pitch —See: *Pitch, hydrodynamic*.
Hydrodynamic pitch angle —Synonymous with hydrodynamic flow angle. See: *Angle, hydrodynamic flow*.
Hydrodynamic spindle toque —See: *Spindle torque, hydrodynamic*.
Hydrofoil —A structure externally similar to an airplane wing designed to produce lift and which operates in water.
Hydrofoil section —The cross-section shape of a hydrofoil.
Ideal angle of attack See: *Angle of attack, ideal*.
Immersion (h_0) [-]—The depth of submergence of the propeller measured vertically from the shaft axis to the free surface.
Immersion ratio [-]—The depth of submergence of the propeller axis divided by propeller diameter.

Inboard rotation —A propeller which is not located on the centreline of the ship is said to have inboard rotation if the blade moves toward the centreline as they pass the upper vertical position. The opposite direction of rotation is called outboard rotation. Also called inward and outward rotation respectively.

Induced velocity, axial (U_A) [LT^{-1}] —The change in the velocity component in the direction parallel to the propeller axis due to the presence of the propeller but not including any change in the wake field due to propeller/hull interactions. Positive upstream. (See Figure 4-1)

Induced velocity, radial (U_R) [LT^{-1}] —The change in the velocity component in the radial direction due to the presence of the propeller but not including any change in the wake field due to propeller/hull interactions. Positive outward

Induced velocity, tangential (U_T) [LT^{-1}] —The change in the velocity component in the tangential direction due to the presence of the propeller but not including any change in the wake field due to propeller/hull interactions. Positive clockwise looking forward. (See Figure 4-1)

Inward rotation —See: *Inboard rotation*.

Kort nozzle —See: *Propeller types (ducted)*.

Leading edge [-]—Blade edge directed to the inflow under normal operating conditions starting from the blade root and ending at the blade tip. (See Figure 4-13).

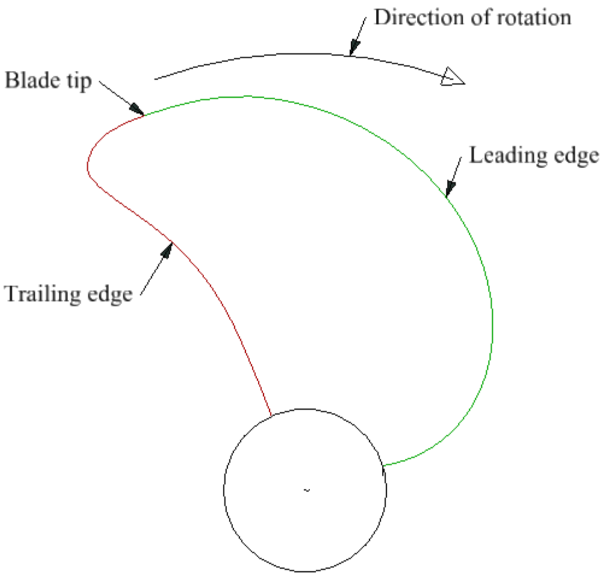


Figure 4-13: Leading and Trailing edges of a propeller blade.

Left handed propeller —A propeller which rotates in the counterclockwise direction when viewed from astern.

Lift (L) [MTL^{-2}] —The fluid force acting on a body in a direction perpendicular to the motion of the body relative to the fluid.

Mean chord length —See: *Chord length, mean*.

Mean line —The mean line is the locus of the midpoint between the upper and lower surface of an airfoil or hydrofoil section. The thickness is generally measured in the direction normal to the chord rather to the mean line. The maximum distance between the mean line and the chord line, measured normal to the chord line, is called the camber. The term camber line is often used synonymously with mean line. (See Figure 4-8)

Mean pitch —See: *Pitch, mean*.

Mean width ratio [-]—Mean expanded or developed chord of one blade divided by the propeller diameter. Equal to the inverse of one half the aspect ratio for a wing.
Median line —Synonymous with generator line.
Nominal pitch —See *Pitch, nominal*.
Nose-tail line —Synonymous with chord line.
Nozzle —The duct portion of a ducted propeller. Synonymous with duct or shroud.
Ogival section —A type of an airfoil or hydrofoil section having a straight face, a circular arc or parabolic back, maximum thickness at the mid chord, and relatively sharp leading and trailing edges.
Outboard rotation —A propeller which is not located on the centreline of the ship is said to have outboard rotation if the blades move away from the centreline as they pass the upper vertical position. The opposite direction of rotation is called inboard rotation. Also called outward and inward rotation respectively.
Outward rotation —See: *Outboard rotation*.
Pitch (P) [L] —The pitch of a propeller blade section at the radius r is given by: $P = 2\pi r \tan\varphi$ where φ is the angle between the intersection of the chord line of the section and a plane normal to the propeller axis. This angle is called the pitch angle. Also called geometric pitch (which see). (See Figure 4-14).

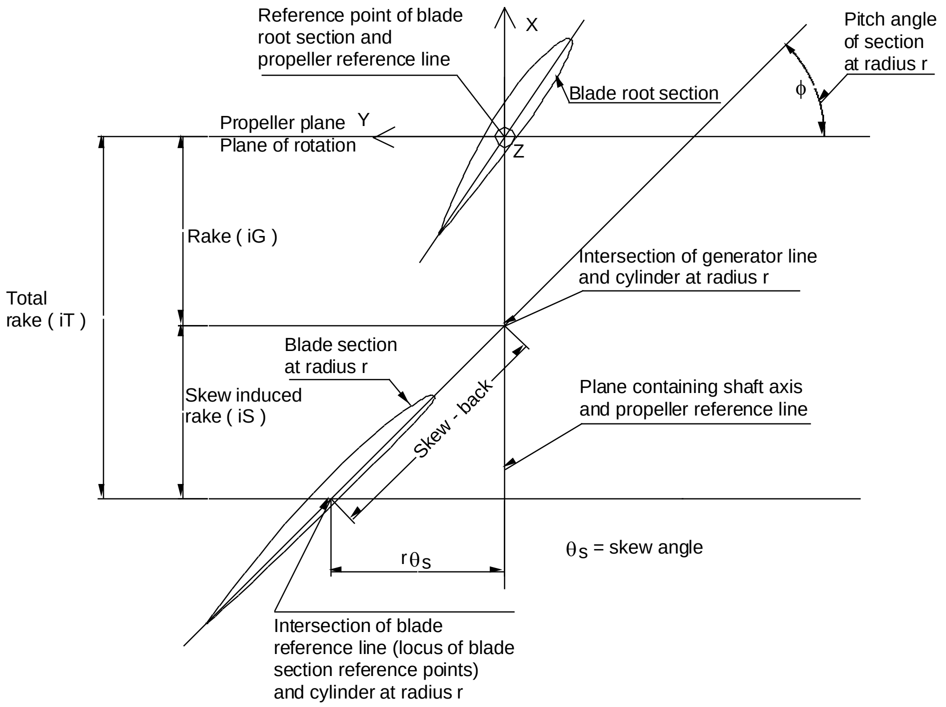


Figure 4-14: View of unrolled cylindrical sections at blade root and at any radius r of a right-handed propeller (looking down) showing recommended position of propeller plane.

Pitch analysis —Advance per revolution at zero thrust as determined experimentally.
Pitch angle (φ) [-]—See: *Pitch*.
Pitch, effective —Weighted value of geometric pitch when pitch is not constant. Both the radius and the thrust distribution (if known) have been used as weighting factors.
Pitch, face —The pitch of a line parallel to the face of the blade section. Used only for flat faced sections where offsets are defined from a face reference line.

Pitch, geometric —The pitch of the nose-tail line (chord line). It is equal to the face pitch if the setback of the leading and trailing edges of the section are equal.

Pitch, hydrodynamic —The pitch of the streamlines passing the propeller including the velocities induced by the propeller at a radial line passing through the midchord of the root section. See: *Angle, hydrodynamic flow*.

Pitch, mean

i. Generally synonymous with the effective pitch.

ii. The pitch of a constant pitch propeller which would produce the same thrust as a propeller with radially varying pitch when placed in the same flow.

Pitch, nominal —Synonymous with face pitch. (See: *Pitch, face*).

Pitch ratio (p)[-] —The ratio of the pitch to the diameter of the propeller. Generally, the face pitch or geometric pitch at the 70 percent radius is used to compute the pitch ratio. Any measure of pitch can be used with the diameter to form a pitch ratio.

Pitch, variable —A propeller blade for which the pith is not the same at all radii is said to have variable pitch or varied pitch. A propeller which has the same pitch at all radii is said to be a constant pitch propeller.

Plane rotation —See: *Propeller plane*.

Pod —Pods are devices which combine both propulsive and steering functions in one device. They are usually located below the stern of a ship (see Figure 4-15).

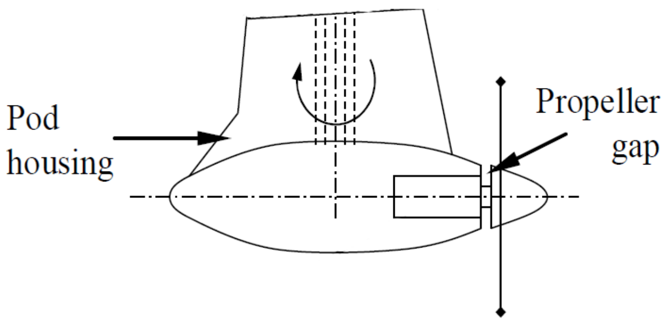


Figure 4-15: Pod.

Power coefficient, delivered (K_P) [-]—The delivered power at the propeller, P_D, expressed in coefficient form:

$$K_P = P_D/\rho n^3 D^5$$

where ρ is the mass density of the fluid, n is the rate of the propeller rotation, and D is the diameter of the propeller.

Power coefficient, Taylor's (B_P) —The horsepower absorbed by the propeller, P_D, expressed in coefficient form:

$$B_P = n(P_D)^{1/2}/(V_A)^{5/2}$$

where n is revolution per minute and V_A is the speed of advance in knots.

Power coefficient, Taylor's (B_U) —The thrust horsepower delivered by the propeller, P_T, expressed in coefficient form:

$$B_U = n(P_T)^{1/2}/(V_A)^{5/2}$$

where n is the revolution per minute and V_A is the speed of advance in knots.

Power loading coefficient (C_P) [-]—The power absorbed by the propeller, P_D, expressed in coefficient form:

$$C_P = \frac{P_D}{\frac{\rho}{2} V_A^3 (D^2/4)} = (K_Q/J^3)(8/\pi)$$

where ρ is the fluid density, V_A is the speed of advance, and D is the propeller diameter. This coefficient may be defined in terms of the ship speed V and is then denoted by the symbol C_{PS}. K_Q and J are the torque and advance coefficient respectively (which see).

Pressure side The side of the propeller blade having the greater mean pressure during normal ahead operation. Synonymous with the face of the blade. Analogous to the lower surface of a wing. (see Figure 4-3)

Projected area —See: *Area, projected*.

Projected area ratio (a_P) [-] —The ratio of the projected area to the disc area.

Propeller —Most generally, any device which will produce thrust to propel vehicle. The most common form is the screw propeller, which basically consists of a central hub and a number of fixed blades extending out radially from the hub (see Figure 4-16). Lift is generated by the blades when the propeller is rotated. One component of the lift force produces the desired thrust and the other component creates torque which must be overcome by the engine to sustain rotation.

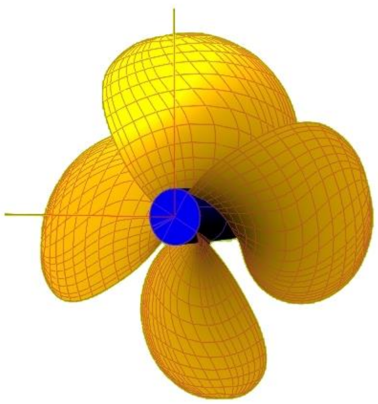


Figure 4-16: Screw propeller.

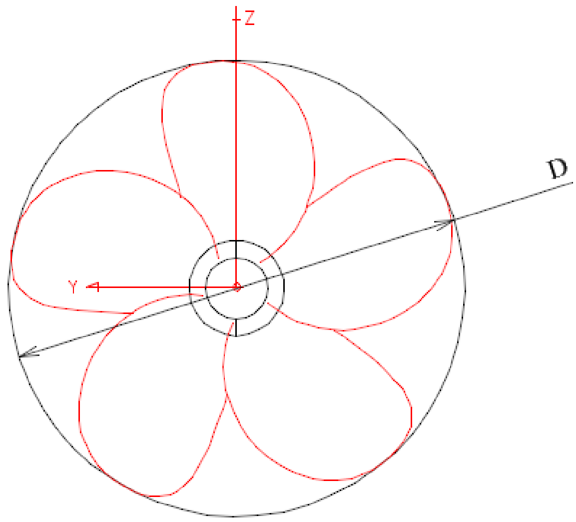


Figure 4-17: Propeller disk, looking forward.

Propeller diameter (D)[L] —The diameter of the propeller disk. (See Figure 4-17)

$$D = 2R$$

Propeller disk —The disk enclosed by the circle passing through the tips of the blades. (See Figure 4-17)

Propeller plane —The plane normal to the shaft axis and containing the propeller reference line, i.e. contain the reference point of the root section. Also called the plane of rotation. (See Figure 4-14 and Figure 4-21).

Propeller radius (R)[L] —The largest distance from the shaft axis (x axis) of the extreme point of a blade (i.e. blade tip). Half the diameter of the propeller disk. (See Figure 4-18).

$$R = \frac{D}{2}$$

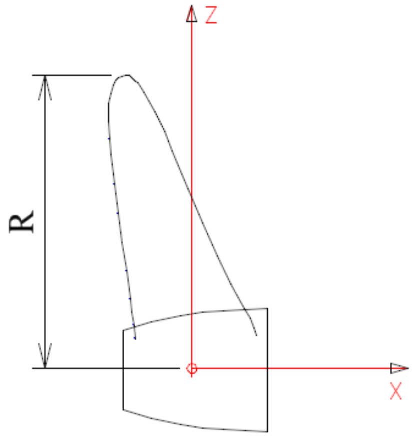


Figure 4-18: Propeller radius.

Propeller reference system, cylindrical —θ angular coordinate, originating from z axis of the rectangular reference system, directed in the same direction as the direction of rotation of the propeller; r radial coordinate; x axis coincides with that of the rectangular reference system. (See Figure 4-19).

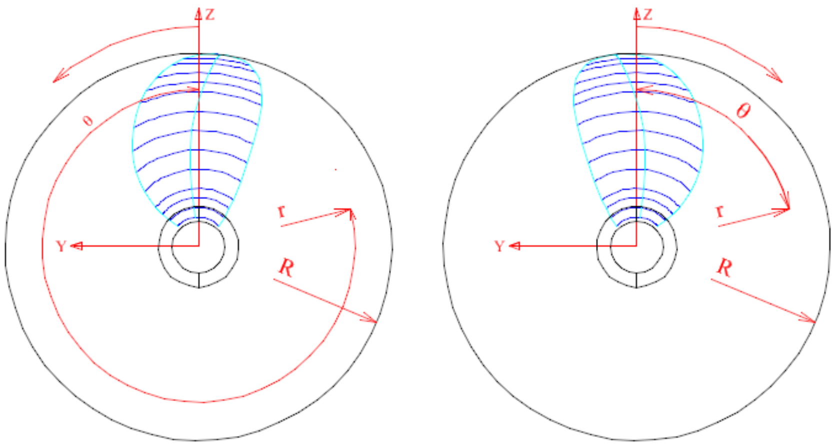


Figure 4-19: Propeller reference system, cylindrical, looking forward.

Propeller reference system, rectangular —x axis along the shaft centre line, directed forward; y axis normal to x and directed to port; z axis normal to x and y in order to form a right-handed Cartesian system, directed upward. The z axis is positioned to pass through the reference point of the root section of a blade. This reference system is unchanged for right-handed and left-handed propellers. (See Figure 4-20).

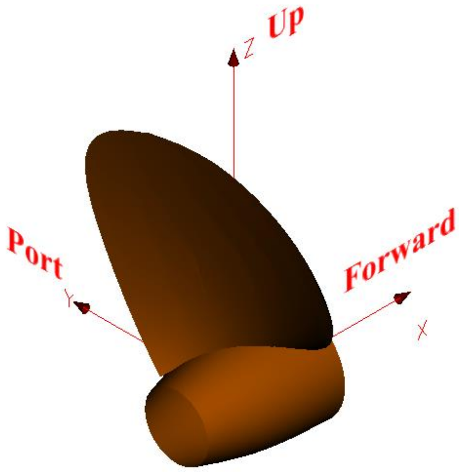


Figure 4-20: Propeller reference system, rectangular.

Propeller types

The basic screw propeller may be described as fixed pitch, subcavitating, open (unducted), and fully submerged. Variations on this basic type are listed below.

Adjustable-pitch propeller —A propeller whose blades can be adjusted to different pitch settings when the propeller is stopped.

Contrarotating propeller — Two propeller rotating in opposite directions on coaxial shafts.

Controllable pitch propeller — A propeller having blades which can be rotated about a radial axis so as to change the effective pitch of the blade while the propeller is operating. This allows full power to be absorbed for all loading conditions. If the pitch can be adjusted to the extent that reverse thrust can be achieved without reversing the direction of rotation of the shaft then the propeller is sometimes called a controllable reversible pitch propeller.

Cycloidal propeller — A propeller consisting of a flat disc set flush with the under surface of the vessel with a number of vertical, rudder-like blades projecting from it. The disc revolves about a central axis and each of the blades rotates about its own vertical axis. The axis of each blade traces a cycloidal path. The blade motion can be varied so as to produce a net thrust in any desired direction in a plane normal to the axis of rotation. It is used where excellent manoeuvrability is required.

Ducted propeller — A propeller with a short duct mounted concentrically with the shaft. The duct, or nozzle is shaped so as to control the expansion or contraction of the slipstream in the immediate vicinity of the propeller. In one form (the Kort nozzle) the flow is accelerated, whereas in the other form (pump jet) the flow is decelerated. A pump jet is sometimes also defined as a ducted propeller with stator vanes regardless of whether the flow is accelerated or decelerated.

Fully cavitating propeller — A propeller designed to operate efficiently at very low cavitation numbers where a fully developed cavity extends at least to the trailing edge of the blade. The blade sections of such propellers have relatively sharp, leading edges for more efficient supercavitating operation and thick trailing edges for strength. Also known as supercavitating propeller.

Interface propeller — A propeller of the fully cavitating ventilated type designed to operate with only a portion of the full disc area immersed. These propellers are considered for high speed applications to vehicles such as surface effect ship where the appendage drag associated with the shafts and struts of a fully submerged propeller would result in a considerable increase in resistance. Also known as partially submerged or surface propellers.

Ring propeller — A propeller with a very short duct attached to the tips of the blades and rotating with the propeller. Also called a banded propeller.

Steerable ducted propeller - A ducted propeller in which the duct can be pivoted about a vertical axis so as to obtain a steering effect.

Supercavitating propeller — See: *Fully cavitating propeller*.

Tandem propeller — Two propellers fitted to the same shaft, one behind the other, and rotating as one.

Ventilated propeller — A propeller of the fully cavitating type, but with provision to introduce air into the cavities in order to achieve fully developed, stable cavities at lower speed than would otherwise be impossible.

Vertical axis propeller — Synonymous with cycloidal propeller.

Pumpjet —See: *Propeller Types (ducted)*

Race, propeller —The accelerated, turbulent column of water forming the outflow from a screw propeller.

Radial induced velocity —See: *Induced velocity, radial.*

Radius (r)[L] —Radius of any point on propeller

Rake (i_G, R_k (ISO)) [L] —The displacement, i_G, from the propeller plane to the generator line in the direction of the shaft axis. Aft displacement is considered positive rake (See Figure 4-14 and Figure 4-21). The rake at the blade tip or the rake angle are generally used as measures of the rake.

Rake angle —The rake angle is defined as:

$$\theta = \tan^{-1}[i_G(r)/r]$$

where r is the radius (See Figure 4-21).

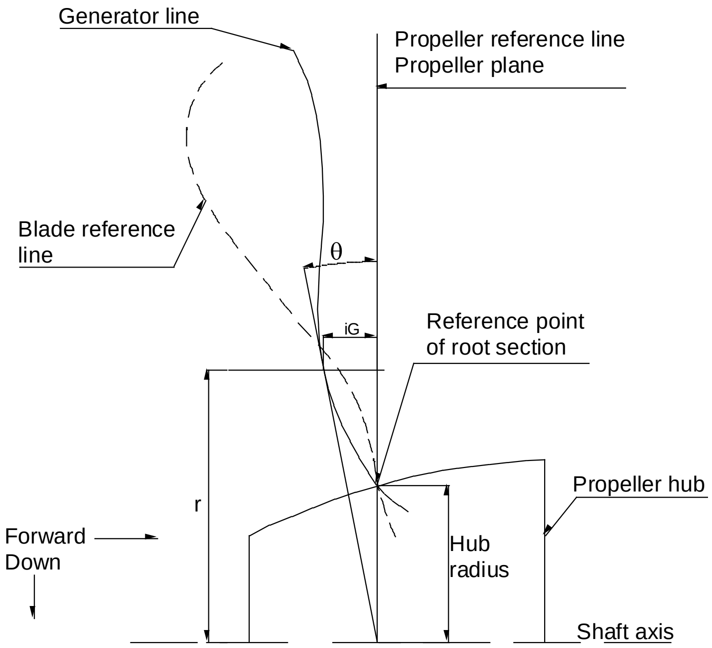


Figure 4-21: Diagram showing recommended reference lines (looking to port).

Rake, skew induced (i_S) [L] —The amount of axial displacement (rake) of a blade section which results when skew-back is used (See Figure 4-14). It is the distance, measured in the direction of the shaft axis, between the generator line and the blade reference line and is given by: $r\theta_S tan\varphi$, where r is the local radius, θ_S is the local skew angle, and φ is the local pitch angle. It is positive when the generator line is forward of the blade reference line.

Rake total (i_T) [L] —The sum of the rake and skew-induced rake (See Figure 4-14)

Reference line, blade —The locus of the reference points of the blade sections (See Figure 4-21 and Figure 4-22). Sometimes used synonymously with generator line.

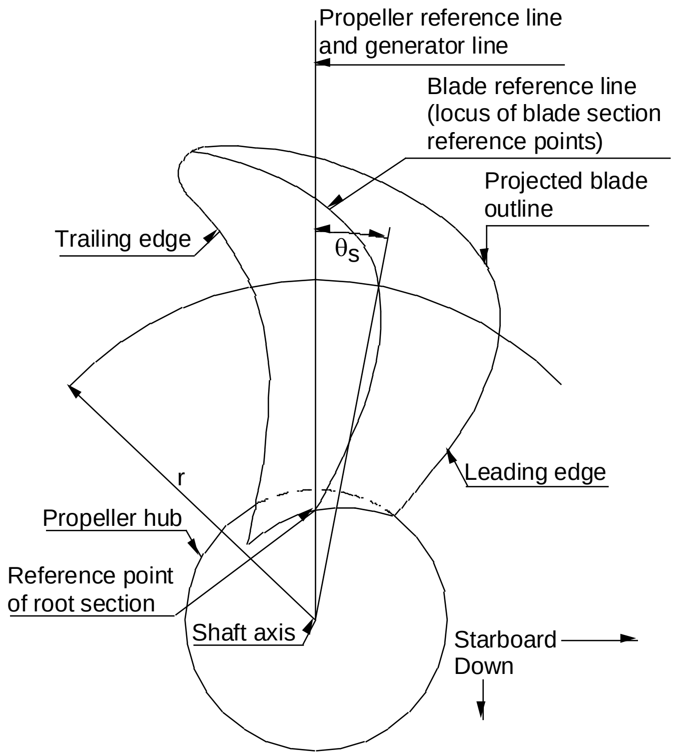


Figure 4-22: Diagram showing recommended reference lines (looking forward).

Reference line, propeller —The straight line, normal to the shaft axis, which passes through the reference point of the root section (See Figure 4-21 and Figure 4-22). It lies in the plane containing the shaft axis and the generator line.

Reference point, blade section —The point on the pitch helix to which the blade section offsets are referred. It usually the mid-point of the chord line. The point of maximum thickness and the location of the spindle axis for controllable pitch propeller, as well as other points, have also been used as blade section reference points. (See Figure 4-7)

Right handed propeller —A propeller which rotates in the clockwise direction when viewed from astern.

Root —The part of the propeller blade adjacent to the propeller hub.

Rudder —See Ship Geometry section.

Rudder, active —A propulsion device installed in the rudder for ship manoeuvring at low or zero speed.

Screw propeller —See: *Propeller*.

Set back (-) [L] —The displacement of the leading edge or trailing edge of a propeller blade section from the face pitch datum line when the section shape is referenced to that line. Also called wash-up. It is called wash-down if negative. The set back ratio is the set back divided by the chord length.

Shock free entry —See: *Angle of attack, ideal*.

Shroud —The duct portion of a ducted propeller concentric with the axis of rotation of the propeller blades. In some cases the duct may be rotated about a vertical axis to provide steering forces. Synonymous: duct, nozzle.

Singing —Intense discrete frequency sound radiated from the propeller due to resonant vibrations of the blades. Generally thought to be due to the shedding of Karman vortices from the trailing edge of the blades at a resonant frequency of the blade vibration.

Skew (c_S) [L] —The displacement of any blade section along the pitch helix measured from the generator line to the reference point of the section (See Figure 4-9). Positive skew-back is opposite to the direction of ahead motion of the blade section. Also called skew-back. Sometimes used (incorrectly) to denote the skew angle.

Skew angle (θ_S) [-]—The angular displacement about the shaft axis of the reference point of any blade section relative to the generator line measured in the plane of rotation (See Figure 4-22 and Figure 4-14). It is positive when opposite to the direction of ahead rotation. This angle is the same as the warp. The skew angle at the blade tip is often used as a measure of the skew-back of a propeller.

Skew-back (-) [L] —The displacement of any blade section along the pitch helix measured from the generator line to the reference point of the section (See Figure 4-14). Positive skew-back is opposite to the direction of ahead motion of the blade section. Also called skew.

Skew-induced rake —See: *Rake, skew induced*.

Slipstream —See: *Race*.

Span (b) [L] —The distance from tip to tip of a hydrofoil. The distance from root to tip is the semi-span. (See Figure 4-23).

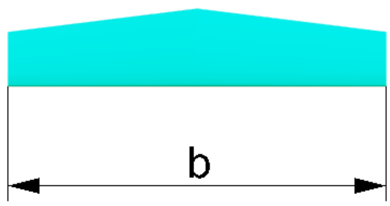


Figure 4-23: Foil span.

Speed of advance (V_A) [LT^{-1}] —The translational speed of the propeller in relation to the body of water into which it is advancing. See also: *Performance Section*.

Spindle axis —The axis about which a controllable-pitch propeller blade is rotated to achieve a change in pitch.

Spindle torque (Q_S) [ML^2T^{-2}] —The torque acting about the spindle axis of a controllable-pitch propeller blade resulting from the hydrodynamic and centrifugal forces exerted on the blade. This torque is positive if tends to rotate the blade toward a higher positive pitch.

Spindle torque, hydrodynamic (Q_{SH}) [ML^2T^{-2}] —The torque acting about the spindle axis of a controllable-pitch propeller blade resulting from the hydrodynamic forces exerted on the blade. This torque is positive if it tends to rotate the blade toward a higher positive pitch.

Spindle torque coefficient, centrifugal (K_{SC}) [-]—The centrifugal spindle torque, Q_{SC}, expressed in coefficient form:

$$K_{SC} = Q_{SC}/(\rho_P n^2 D^5)$$

where ρ_P is the mass density of the propeller blade material, n is the rate of propeller rotation, and D is the propeller diameter.

Spindle torque coefficient, hydrodynamic (K_{SH}) [-]—The hydrodynamic spindle torque, Q_{SH}, expressed in coefficient form:

$$K_{\mathrm{SH}} = Q_{\mathrm{SH}}/(\rho n^2 D^5)$$

where ρ is the mass density of the fluid, n is the rate of propeller rotation, and D is the propeller diameter.

Spindle torque index, hydrodynamic () [-]—The hydrodynamic spindle torque, Q_{SH}, expressed in coefficient form:

$$Q_{\mathrm{SH}}/\left\{\frac{1}{2}\rho[V_{\mathrm{A}}^2 + (0.7nD)^2]\right\}(\pi D^3/4)$$

where ρ is the density of the fluid, V_A is the speed of advance, n is the rate of propeller rotation, and D is the diameter. This form of the spindle torque coefficient is useful when presenting propeller spindle torque characteristics over a range of advance coefficient extending from zero (V_A = 0) to infinity (n = 0). Usually presented as a function of

$$\beta^* = \tan^{-1}[V_{\mathrm{A}}/(0.7\, n\pi D)]$$

Stacking line —Synonymous with generator line. Also used to denote the blade reference line.

Static thrust coefficient —See: *Thrust coefficient, static.*

Steerable ducted propeller —See: *Propeller Types*.

Suction side —The low pressure side of a propeller blade. Synonymous with the back of the propeller blade. Analogous to the upper surface of a wing. (see Figure 4-3)

Supercavitating propeller —See: *Propeller Types*.

Tangential induced velocity —See: *Induced velocity, tangential*.

Taylor's advance coefficient —See: *Advance coefficient, Taylor's*.

Taylor's power coefficient (B_U, B_P) —See: *Power coefficient, Taylor's*.

Thickness, local (t_X) [L] —The thickness of a propeller blade section at any location along the X axis of the section reference system, generally measured in the direction normal to the chord line. (See Figure 4-8).

Thickness, maximum (t) [L] —The maximum thickness of a propeller blade section, generally measured in the direction normal to the chord line. (See Figure 4-8).

Thickness ratio (δ) [-]—The ratio of the maximum thickness, t, of a foil section to the chord length, c, of that section.

Thrust (T) [MLT^{-2}] —The force developed by a screw propeller in the direction of the shaft.

Thrust breakdown —The phenomenon of loss of thrust due to excessive cavitation on a subcavitating type propeller. The torque absorbed by the propeller is affected similarly and is called torque breakdown. Both the thrust and torque coefficient may increase slightly above noncavitating values near the initial inception of cavitation. In general, the changes in thrust and torque are such that propeller efficiency is reduced.

Thrust coefficient (K_T) [-]—The thrust, T, produced by propeller expressed in coefficient form:

$$K_T = T/(\rho n^2 D^4)$$

where ρ is the mass density of the fluid, n is the rate of propeller rotation, and D is the propeller diameter.

Thrust coefficient, static () [-]—A figure of merit for comparing the relative performance of propulsion devices at zero speed given by the equation:

$$\frac{T}{(\rho\pi/2)^{\frac{1}{3}}(P_D D)^{\frac{2}{3}}} = \frac{K_T}{\pi\left(K_Q\right)^{\frac{2}{3}}2^{\frac{1}{3}}}$$

The ideal upper limit for unducted screw propellers is 1.0, while for ducted propellers the upper limit depends upon the area ratio of the down stream diffuser. When the area ratio is unity, i.e. no diffusion or contraction, the limit is $2^{1/3} = 1.26$; ρ is the fluid density, D propeller diameter, P_D delivered power; K_T and K_Q are the thrust and torque coefficients respectively (which see).

Thrust index (C_{T^*}) [-]—The thrust, T, produced by the propeller expressed in coefficient form:

$$C_{T^*} = \frac{T}{\frac{1}{2}\rho\left[V_A^2+(0.7nD)^2\right](\pi D^2/4)}$$

where ρ is the density of fluid, V_A is the speed of advance, n is the rate of rotation and D is the propeller diameter. This form of the thrust coefficient is useful when presenting propeller thrust characteristics over a range of advance coefficients from zero ($V_A = 0$) to infinity ($n = 0$). Usually presented as a function of

$$\beta^* = \tan^{-1}[V_A/(0.7\pi nD)].$$

Thrust loading coefficient (C_{Th}) [-]—The thrust, T, produced by the propeller expressed in coefficient form:

$$C_{Th} = \frac{T}{\frac{\rho}{2}V_A^2\frac{\pi D^2}{4}} = \frac{K_T}{J^2}\frac{8}{\pi}$$

where ρ is the mass density of the fluid, V_A is the speed of advance, D is the propeller diameter, (the symbol C_{TS} is used when this coefficient is based on ship speed instead of speed of advance). Where K_T and J are the thrust and advance coefficient respectively (which see).

Thruster —A propulsion device for zero or low speed manoeuvring of vessels.

Torque (Q) [ML^2T^{-2}] —The torque delivered to the propeller aft of all bearings.

Torque breakdown —See: *Thrust breakdown*.

Torque coefficient (K_Q) [-]—The torque, Q, delivered to the propeller expressed in coefficient form:

$$K_Q = \frac{Q}{\rho n^2 D^5}$$

where ρ is the density of the fluid, n is the rate of propeller rotation, and D is the propeller diameter.

Torque index (C_{Q^*}) [-]—The torque, Q, absorbed by the propeller expressed in coefficient form:

$$C_{Q^*} = \frac{Q}{\frac{1}{2}\rho\left[V_A^2+(0.7nD)^2\right](\pi D^3/4)}$$

where ρ is the density of fluid, V_A is the speed of advance, n is the rate of rotation and D is the *diameter. This form of the torque coefficient is useful when presenting propeller torque* characteristics over a range of advance coefficients from zero ($V_A = 0$) to infinity ($n = 0$). Usually presented as a function of

$$\beta^* = \tan^{-1}[V_A/(0.7\pi nD)].$$

Total rake —See: *Rake, total*.

Trailing edge [-]—Blade edge opposite to the inflow under normal operating conditions starting from the blade root and ending at the blade tip. (See Figure 4-13).

Variable pitch See: —*Pitch, variable*.

Velocity, induced —See: *Induced velocity (axial, tangential, and radial)*.
Ventilated propeller —See: *Propeller Types*.
Vertical-axis propeller—Synonymous with cycloidal propeller. See: *Propeller Types*.
Warp () [-]—Synonymous with skew angle.
Wash-back —See: *Set-back*.
Wash-down —See: *Set-back*.
Wash-up —See: *Set-back*.
Water jet —A form of propulsion in which water is taken into hull of the ship by means of ducting and energy is imparted to the water with a pump. The water is then ejected astern through a nozzle.
Windmilling —The rotation of a propeller caused by flow past the propeller without power being applied to the propeller shaft. This action may take place while the ship is moving under its own momentum, while it is being towed, or while it is being propelled by other means of propulsion.

5. CAVITATION

In this section the term cavitation is defined as the process of formation of the vapour of liquid when it is subjected to reduced pressure at constant ambient temperature. It is used in the engineering context of liquid flow around bodies generally and, in particular, screw-propellers and hydrofoils.

Acceleration zone —In the sequence of cavitation erosion, the zone of the curve of weight loss versus time in which a rapid increase in weight loss occurs (the region between the *incubation zone* and the *deceleration zone* which see). Formerly called the *Accumulation zone*.

Air content —The term used loosely to describe *gas content* (which see) when gas content is composed of components of air in the liquid.

Air content ratio —See: *Gas content ratio*.

Attached cavities —Term applied to cavitation region with fairly well defined line of attachment to the body about which it is formed. It may be a *Fully developed cavity* or *Partial cavity* (which see).

Back cavitation —Cavitation occurring on the suction side (back) of a propeller blade.

Base-vented flow or bodies —Flow in which the body has a fully ventilated, blunt trailing edge while the body itself is fully wetted.

Bubble collapse —The final phase in the life history of a transient cavitation bubble that enters an increasing pressure field collapses and, unless containing considerable foreign gas, disappears. The total life of a transient cavitation bubble is measured in times of the order of milliseconds,

Bubble growth —The initial phase in the life history of a cavitation bubble in which a nucleus become unstable under a pressure reduction and grows explosively (*vaporous cavitation*) or which grows under quasi-equilibrium conditions by diffusion of gas (*gaseous cavitation*).

Bubble rebound —Regrowth, after initial collapse, of a transient cavity that contains considerable permanent gas, due to energy storage in the compressed gas. Several growth and rebound cycles have sometimes been observed.

Bubble surface stability —The stability of the bubble surface. Expanding bubbles are stable. Collapsing bubbles are unstable, being subject to Taylor instability (light fluid accelerated toward a heavier fluid) or distortions produced by body forces in a pressure gradient.

Cavitating flow —A two-phase flow composed of a liquid and its vapour is called a *cavitating flow* when the phase transition is a result of a hydrodynamic pressure change.

Cavitating wakes —Cavitation that occurs in the low pressure cores of the turbulent eddies which make up the wake of a moving body.

Cavitation —In the most engineering contexts, cavitation is defined as the process of formation of the vapour phase of a liquid when it is subjected to reduced pressure at constant ambient temperature. In general, a liquid is said to cavitate when vapour bubbles are observed to from and grow as a consequence of pressure reduction. (See also: *Vaporous cavitation* and *Gaseous cavitation*).

Cavitation damage —Deformation and/or erosion of materials in cavitated regions, associated primarily with the high pressures developed during cavity collapse.

Cavitation inception —Inception of cavitation takes place when nuclei subjected to reduced pressure reach critical size and grow explosively. It is generally described by the ambient pressure at which cavitation starts, or more precisely, by the *Critical cavitation number* (which see).

Cavitation number (σ) [-]—The ratio of the difference between absolute ambient pressure p and cavity pressure p_C to the free stream dynamic pressure q:

$$\sigma = \frac{p - p_C}{q}$$

When the cavity pressure is assumed to be the vapour pressure p_V the term is generally called *Vapour cavitation number* (which see as *Cavitation number, vapour*).

Cavitation number, critical —Often used as an alternate to *Inception cavitation number* (which see as *Cavitation number, inception*).

Cavitation number, inception(σ_I) [-]—The inception cavitation number σ_I is the value of the cavitation number σ at which the inception of cavitation occurs in a flowing system. When $\sigma_I > \sigma$, cavitation will not occur; thus σ_I is the characteristic of the flow geometry while σ is characteristic of the liquid gas system. (In practical system, the definition of σ is usually based on the vapour pressure.) Sometimes also called *Critical cavitation number* (which see as *Cavitation number, critical*).

Cavitation number, vapour (σ_V) [-]—The ratio of the difference between absolute ambient pressure p and vapour pressure p_V to the free stream dynamic pressure q:

$$\sigma_V = \frac{p - p_V}{q}$$

See also: *Cavitation number*.

Cavity drag (D_C) [LMT^{-2}] —The energy expended in forming a fully-developed cavity, which cannot be recovered at cavity closure and hence is exhibited as drag on the body. It is equal to the energy in the re-entrant jet which is dissipated.

Cavity length (l_C) [L] —The streamwise dimension of a fully developed cavitating region, extending from its leading edge (point of attachment) to the point of closure.

Cavity pressure (p_C) [L^{-1}MT^{-2}] —Actual pressure within a steady (or quasi-steady) cavity. Approximately equal to the sum of the partial pressure of vapour and other gases diffused and entrained into the cavity.

Cavity thickness (δ_C) [L] —Maximum dimension of a fully developed cavity normal to the length dimension.

Chemo-luminescence —Visible light produced in the gas vapour of cavities in an ultrasonic field (see: *Sono-luminescence*) caused by chemical reactions associated with high pressure and/or temperatures.

Choked flow —This is defined as the flow condition in which the drag of a body is directly proportional to the square of the upstream velocity and is not a function of the cavitation number. The pressure coefficient at any point on the body is independent of the cavitation number.

Choking cavitation number —This is defined as that value of σ at which a terminal, minimum value of the drag coefficient is found for a cavitating body.

Collapse pressure (p_{AC}) [L^{-1}MT^{-2}] —The pressure produced in the field of a collapsing cavitation bubble estimated to be of the order of thousands of atmospheres at the minimum radius reached before the process stops or rebound begins.

Critical cavitation number —See: *Cavitation number critical*.

Critical pressure (p_{AI}) [L^{-1}MT^{-2}] —The absolute pressure at which cavitation inception takes place, in either a flowing system or an imposed pressure field (as in ultrasonic cavitation). In turbulent flow, the critical pressure will be a function of the average hydrodynamic pressure and the pressure fluctuations associated with turbulence. Sometimes also called *Inception pressure*. (See also: *Gaseous* and *Vaporous cavitation*.)

Critical velocity (U_I) [LT^{-1}] —In a flowing system (or its equivalent: a body moving through a liquid), the free stream velocity at which cavitation inception takes place in a field of constant ambient pressure. In a turbulent flow, the critical velocity is also dependent on the velocity fluctuations associated with turbulence. Sometimes also called *Inception velocity*.

Deceleration zone —In the sequence of cavitation erosion, the zone of the curve of weight loss versus time in which the rate of weight loss decrease (the region following the *acceleration zone*, which see). Formerly called the *Attenuation zone*.

Desinent cavitation —Cavitation under conditions of pressure and velocity such that cavitation will be suppressed by a slight change in the ambient conditions: pressure increase and /or velocity reduction.

Electrolytic effects —Enhancement of cavitation erosion by electrochemical interactions due to local differences in the liquid or metal structure.

Entrained gas content —See: *Gas content*.

Face cavitation —Cavitation occurring on the pressure side (face) of a propeller blade. It is generally a result of operation such that the local blade angle of attack is excessively negative.

Foam cavitation —A cavitated region formed entirely of a mass of transient cavities so as to resemble foam (formerly called *burbling cavitation*).

Free gas content —See: *Gas content*.

Free streamline flow —Fully developed cavity flow. For steady flows, the cavity walls are stream surfaces of the flow with the unique feature that the pressure is constant on the free streamlines. The term originates in the mathematical problem that the boundaries are “free” to be determined by the known condition of constant pressure.

Fully developed cavity— A cavity formed on a body which terminates sufficiently far downstream so that the flow at the downstream region does not influence the body itself. For example, the cavity is fully developed when the re-entrant jet formed at the downstream end of the cavity is dissipated without impinging on the body. See also: *Supercavitating flows*.

Gas content (α) —The gas content of a liquid may be in either a dissolved or undissolved state. The quantity of dissolved gas will vary according to Henry’s law, but it is now generally agreed that cavitation inception is associated with the gas contained in nuclei in an undissolved state (See *Nuclei* and *Nucleation*). Total gas content is equal to both the dissolved and undissolved gas. “Free” and “entrained” gas content are alternate terms for *undissolved* gas content, but the latter term is preferred.

Gas content of the saturated liquid (α_S) —The gas content of the saturated liquid at standard temperature and pressure.

Gas content ratio (a_S) [-]—The ratio of the content (dissolved and undissolved) in a test liquid to the gas content of the saturated liquid at standard temperature and pressure: $a_S = \alpha/\alpha_S$

Gas injection, protection by —Small amounts of gas injected into the cavitating region to reduce the pressure through a “cushioning” effect during compression by the collapsing cavitation bubbles.

Gaseous cavitation —Depending upon the magnitude of the pressure reduction and the rate of application, a bubble may grow slowly by diffusion gas into the *nucleus* (which see) and contain mostly gas rather than vapour. Such bubble growth is defined as gaseous cavitation. Such cavitation may occur at pressure greater or less than vapour pressure aided by the process of *Rectified diffusion* (which see).

Hub cavitation —See: *Hub vortex cavitation*.

Hub vortex cavitation —Cavitation in the vortex produced by the blades of a propeller at the hub.

Hysteresis, cavitation —Difference between critical cavitation numbers for incipient and desinent cavitation. Also, the difference between the angle of attack of a lifting surface for initiation or fully developed cavitation during angle of attack increase and the much lower angle of attack at which a fully developed cavity can still be maintained once it has been formed.

Inception of cavitation —See: *Cavitation inception*.

Inception cavitation number —See: *Cavitation number, inception*.

Inception pressure —See: *Critical pressure*.

Inception velocity —See: *Critical velocity*.

Incipient cavitation —Cavitation which just begins with a slight change in ambient conditions: pressure decrease and/or velocity increase.

Incubation zone —In the sequence of cavitation erosion, the initial zone of the curve of weight loss versus time in which the material undergoes changes (e.g. work hardening in ductile metals) due to repeated bubble collapse pressures, but in which the material suffers little or no weight loss.

Intensity damage —The power absorbed per unit eroded area of a specimen undergoing erosion.

Intermittent cavitation —A type of cavitation that respectively originates and disappears from a discrete point on a solid surface.

Internal jets —Jets sometimes formed by the unsymmetrical collapse of transient cavities. Also sometimes called *microjets*.

Jet cavitation —Cavitation formed in the low pressure eddies associated with the turbulent fluctuations in the high shear region of jet flows.

Laminar cavitation —See: *Sheet cavitation*.

Microjets —See: *Internal jets*.

Non-stationary cavities —Free-streamline (cavitating) flows in which the cavity size is a function of time. The cavity surface is a boundary surface, but not necessarily a stream surface. Cavities trailing a body entering a water surface are characteristic of non-stationary cavities.

Nucleation —The process of formation of nuclei in liquid. Also, sometimes used to refer to the process of stabilisation of nuclei to account for their persistence in undersaturated and saturated liquids.

Nucleus, nuclei —Small bubbles, often sub-microscopic in size, containing permanent gas and/or the vapour of the liquid, which are required for inception of cavitation at the pressure near vapour pressure. (See also: *Nucleation*).

Onset cavitation —See: *cavitation inception.*

Orange peel surface appearance —Description of a surface moderately damaged by the cavitation in which the appearance is that of the surface of the Jaffa or California orange.

Partial cavities —Quasi-steady cavities that extend only partially along the bodies about which they are formed.

Pitted surface appearance —Description of a surface damaged by cavitation in which pits are formed either by crater-like deformation (especially as in lead) without loss of material or by actual loss of material following work hardening or fatigue.

Propeller-hull vortex cavitation —Propeller tip vortex cavitation that extends intermittently to the surface of hull.

Protective coating —Metallic and non-metallic materials applied to reduce surface damage by cavitation. They may be welded, sprayed or bonded to the surface.

Pseudo cavitation —Growth and collapse of gas filled bubbles whose size is at all times in static equilibrium with the surrounding pressure field.

Pulsating cavity —A “pulsating” cavity is a ventilated cavity which exhibits self-excited oscillations of the cavity surface as a resonance phenomenon of the gas-liquid (cavity-jet) system; i.e. for self-sustained oscillations, the frequency of the volume changes due to travelling surface waves on the cavity wall (and, hence, corresponding pressure changes) must be equal to the natural frequency of the gas liquid system.

Rate of weight loss —The primary criterion for cavitation erosion, i.r., the weight loss per unit time from a test specimen.

Rectified diffusion —Term applied to the net mass transport into a bubble of gas dissolved in a saturated liquid when the liquid is subjected to an oscillating pressure field.

Re-entrant jets —The re-entrant (upstream) flow at the trailing edge of steady (quasi-steady) cavities. Also, the re-entrant flow associated with the closure of non-stationary cavities formed about missiles entering a water surface.

Root cavitation —Cavitation in the low-pressure region of the blade roots on a marine propeller.

Screening effect—Effect associated with the "screening" of nuclei by the pressure gradient about the body to which the nuclei are being convected, thus determining which nuclei will be repelled from and which nuclei will be swept into regions where the pressure are such as to enable cavitation inception to take place.

Sheet cavitation —A term applied to describe relatively thin, steady or quasi-steady cavities. (Also, formerly called *laminar cavitation*)

Sono-luminescence —Visible light produced in the gas or vapour of cavities generated in the alternating pressure of an ultrasonic field. This phenomenon is believed to be associated with high temperatures resulting from compression of the gases within the bubble.

Spongy surface appearance —Description of a surface badly damaged by cavitation in which erosion has taken place to a considerable depth and has the appearance of a sponge. This description is particularly characteristic of brittle materials and other materials after long exposure.

Spot cavitation —A general term for narrow quasi-steady cavities attached to a surface.

Steady quasi-steady cavities —Cavitating flow may be composed of individual transient cavities or of large cavities attached to the body on which cavitation has been induced (particularly if the detachment point is sharply defined, as for hydrofoil with sharp leading edge). The envelope of the bubbles in the former case and the cavities in the latter case are quasi-steady in the sense that envelope or cavity surface is stationary on a temporal average.

Steady zone—In the sequence of cavitation erosion, the final zone of the curve of weight loss versus time, in which the rate of weight loss is nearly constant. (Also called *steady-state zone*).

Streak cavitation —Narrow quasi-steady cavities formed about excrescences or isolated roughness near the leading edge of a hydrofoil or other body. Such cavitation may also be associated with pressure variations in unstable laminar boundary layers.

Stream nuclei —Undissolved gas nuclei existing in a stabilised condition (either on dust particles or otherwise) which are convected by the stream into regions of low pressure where they form cavitation sources.

Supercavitating flows —Cavity flows in which attached, fully developed cavities extend beyond the trailing edge of the body about which the cavity is formed. (See also: *Attached cavities* and *Fully developed cavities*).

Supercavitation —Term sometimes used as synonymous with *Supercavitating flow* (which see).

Superventilation; Superventilated flow —Terms analogous to Supercavitating flow to denote a ventilated flow in which the cavity extends beyond the trailing edge of the body about which the cavity is formed.

Thoma number(*Th*) [-] —The ratio of the difference between total head and the vapour pressure (upstream of the impeller of rotating machinery) to the total head produced or absorbed by the machine.

Tip cavitation —Surface cavitation which occurs near the tip propeller blade.

Tip vortex cavitation —Cavitation occurring in the low-pressure core of the tip vortex of a hydrofoil or propeller.

Total gas content —See: *Gas content*.

Trailing vortex cavitation —Persisting cavitation in the low-pressure core of trailing vortices downstream of hydrofoils or propellers. (See also: *Tip vortex cavitation* and *Hub vortex cavitation*).

Transient cavities —Cavitation bubbles that grow from nuclei, sometimes oscillate (if containing a high volume of permanent gas component) and eventually collapse and disappear.

Trapped gas —Undissolved gas trapped in the cavities of foreign particles or the crevices of the boundary under study.

Unsteady cavities — Attached cavities which alternately grow (resembling steady cavities at any instant) – extending downstream from the point of attachment and collapse (i.e. sudden reduction in length), presumably by cyclic filling by the re-entrant flow and subsequent re-evaporation.

Vapour cavitation number —See: *Cavitation number, vapour*.

Vaporous cavitation —A *nucleus* (which see) that grows explosively (after reaching critical size) contains mostly vapour phase, the diffusion time being too short for any significant increase in gas volume. This process, which depends upon evaporation of the liquid into the growing bubble, is a true cavitation and is called *vaporous cavitation*. For such cavitation to occur, pressure below vapour pressure are required.

Ventilated flow —A ventilated flow is one in which a "cavity" is formed entirely with air (or other permanent gas).

Ventilation —Process by which a ventilated flow is formed and maintained. *Natural ventilation* is applied to a ventilated flow which derives a continuous flow of gas by means of the pressure created by the flow itself, as from the free surface in the case of a surface piercing, ventilated strut. *Forced ventilation* is applied to a ventilated flow in which the permanent gas is continuously supplied into the cavity by auxiliary means such as a pump.

Ventilation inception —Ventilation inception is defined as the condition at which air (or permanent gas) is drawn into the low-pressure region in a non-cavitating flow, from an external source, as at the free surface of a liquid.

Ventilation index —The ratio of the volumetric air feed rate to the product of free stream velocity and an area proportional to the cavity cross sectional dimension or to some typical body dimension.

Volume loss (V_L) [L^3] —An alternative criterion to weight loss for assessing cavitation damage, often derived from weight loss by using the density of the specimen material.

Vortex cavitation —See: *Hub vortex cavitation*, *Tip vortex cavitation* and *Trailing vortex cavitation*.

Wall nuclei —The undissolved gas nuclei which may exist in equilibrium in the crevices of the boundary wall material.

Weight loss (W_L) [LMT^{-2}] —Weight of material actually eroded from a specimen during a specified time while undergoing erosion damage. The most widely used measure of cavitation damage.

6. SEAKEEPING

In this section the term seakeeping covers, in general, the behaviour and performance of a ship in a seaway including, in particular, ship motions and the sea states which cause them.

Added mass [M] —The total hydrodynamic force, per unit acceleration, exerted on a ship or other body in phase with and proportional to the acceleration.
Added mass coefficient (*Aij*) [-]—A non-dimensional coefficient expressing *added mass* (which see) in ith mode due to jth motion.
Amplitude —Extreme value of a sinusoidal quantity with respect to the mean value.
Angle of drift or sideslip —See: *Drift or sideslip, angle of.*
Angle of heel or list —See: *Heel or list, angle of.*
Angle, leeway —See: *Drift or sideslip, angle of.*
Angle, pitch —See: *Pitch angle.*
Angle, roll —See: *Roll angle.*
Angle of trim —See: **Trim, angle of**
Angle of wave direction —See: *Wave direction, angle of*
Angle of wave encounter —See: *Wave encounter, angle of*
Angle, yaw —See: *Yaw angle.*
Apparent —Referring to wave characteristics, a visible property of an irregular wave record as distinguished from a property of the components waves. Thus, an apparent wave height is a particular peak-to-trough distance.
Auto correlation —The correlation between a random function of time, or space, and the same function shifted in time, or space, by a specified "lag" τ. The normalised auto correlation function is the auto covariance divided by the variance.
Bilge keel —See: Ship geometry section under *Keel*.
Broaching —An involuntary and dangerous change of heading produced by a severe following sea.
Celerity —See: *Wave speed.*
Coherency —A measured of the linear dependency of two random functions of time, or space, analogous to a correlation coefficient.
Coupling —Influence of one mode of motion on another mode of motion, for instance, coupling between heave and pitch.
Covariance —Average of squares of the deviations from the mean value.
Cross-correlation —The correlation between two random functions of time, or pace, with one shifted in relation to the other by a "lag" τ.
Damping —A characteristic property of a dynamic system, which dissipates energy and reduces the motion.
Damping coefficient —Ratio of damping force or moment amplitude as a function of frequency.
Drift —That motion, or component of motion, caused by some action other than that of the main propulsion devices of a ship, such as wind, waves, current and like. See also: *Sideslip*.
Drift or sideslip, angle of (β) [-]—The horizontal angle between the instantaneous direction of motion of the centre of gravity of a ship and its longitudinal axis. It is positive in the positive sense of rotation about the vertical body's axis.
Emergence () [L] —The relative vertical distance of a part (usually the bow) of an oscillating ship above the water surface; opposite to submergence.
Factor, magnification —The ratio of the output amplitude at a certain frequency to the static response.

Factor, tuning (Λ) [-]—Ratio of excitation frequency to natural frequency or ratio of natural period of a motion to period of encounter. The tuning factor in heave, pitch and roll have the symbol,

$$\Lambda_Z = \frac{\omega_\mathrm{E}}{\omega_Z} \quad \Lambda_\theta = \frac{\omega_\mathrm{E}}{\omega_\theta} \quad \Lambda_\varphi = \frac{\omega_\mathrm{E}}{\omega_\varphi}$$

or

$$\Lambda_Z = \frac{T_\mathrm{Z}}{T_\mathrm{E}} \quad \Lambda_\theta = \frac{T_\theta}{T_\mathrm{E}} \quad \Lambda_\varphi = \frac{T_\varphi}{T_\mathrm{E}}$$

respectively

Flare —See: *Ship Geometry Section*.

Force, damping —A force which tends to reduce the motion and, if assumed to be linear, is proportional to the velocity.

Force exciting —A fluctuating external force that causes motion of body, as for instance, a ship when encountering a train of waves.

Force, restoring —A force tending to return a body to its initial condition when displaced by an external force.

Force, wave shearing, horizontal or lateral (F_L) [MLT^{-2}] —That part of the inertial lateral shearing force acting on a cross section of a hull that is caused by the action of waves and ship motions.

Force, wave shearing, normal or vertical (F_N) [MLT^{-2}] —That part of the inertial vertical shearing force acting on a cross section of a hull that is caused by the action of waves and ship motions.

Freeboard (f) [L] —See: *Ship Geometry Section*.

Frequency (f) [T^{-1}] —The number of cycles occurring per unit of time.

Frequency, circular (ω) [T^{-1}] —In any cyclic motion, or in any periodic motion which may be represented by a cyclic motion, the circular frequency is the angular velocity. If ω is in radiant per second, then,

$$\omega = \frac{2\pi}{T} \text{ and } f = \frac{\omega}{2\pi}$$

where T is the period and f is the frequency.

Frequency of wave (f_W) [T^{-1}] —The number per unit time of successive crests of a train of waves at a fixed angle of encounter, μ; the reciprocal of the wave period T_W.

Frequency of wave encounter (f_E) [T^{-1}] —The number per unit time of successive crests of a train of waves meeting a fixed point of a ship, at a fixed angle of encounter, μ; the reciprocal of the period of encounter T_E. In deep water:

$$f_\mathrm{E} = f_\mathrm{W} + \frac{2\pi}{g} V f_W^2 \cos\mu$$

where f_W is wave frequency and V ship speed.

Frequency of wave encounter, circular (ω_E) [T^{-1}] —

$$\omega_\mathrm{E} = \frac{2\pi}{T_\mathrm{E}} = 2\pi f_\mathrm{E}$$

Frequency, natural, of heave, pitch or roll of a ship (f_Z, f_θ, or f_φ) [T^{-1}] —The frequency of the periodic heaving, pitching or rolling motion of a ship.

Frequency, natural circular, of heave, pitch or roll (ω_Z, ω_θ or ω_φ) [T^{-1}] —Frequency, natural circular, of heave, pitch or roll has the following definitions respectively:

$\frac{2\pi}{T_Z}$, $\frac{2\pi}{T_\theta}$, and $\frac{2\pi}{T_\varphi}$, where T_Z, T_θ and T_φ are the natural periods (which see).

Green water —Water shipped on the deck of a ship in heavy seas, as distinct from spray.
Group velocity —The average rate of advance of the energy of a finite train of gravity waves.
Gyradius (radius of gyration) (k_X, k_{XX}, k_Y, k_{YY}, k_Z, k_{ZZ}) [L] —The square root of the ratio of mass moment of inertia (referred to body axes) to the mass of a body. See General Section for body axes under *Axes, co-ordinate*.
Harmonic —Sinusoidal, in referring to a function or motion.
Heading (ψ) [] —The instantaneous direction of the projection of the forward longitudinal axis of a ship in a horizontal plane, defined by degrees of the compass or degrees azimuth. See also Figure 7-2.
Heaving —The vertical oscillatory motion of a specified point in a vessel, usually the centre of gravity. Although the heaving of a ship is a motion which is confined to operation in waves, it is possible with a high-speed planing craft for such motion to occur in calm water under some conditions. (See *Porpoising*)
Heave to —To maintain control of a ship, especially in extremely heavy weather, with minimum possible speed through the water.
Heel or list —A steady inclination of a ship about a longitudinal axis; to be distinguished from rolling, which is an oscillatory motion.
Heel or list, angle of (ϕ) [-]—The angle, measured about a longitudinal axis, between a static inclined position of a ship and its normal upright position.
Hydroelasticity —Analogous to aeroelasticity. The study of the interaction between the inertial, hydrodynamic and elastic forces in a structure subjected to hydrodynamic loading. Divided into dynamic hydroelasticity, where these three forces are co-existent, or static hydroelasticity where inertial forces are absent.
Impact —The sudden contact of body or ship, or any part thereof, with the surface of a liquid.
Leeway —The downwind or down sea motion of a ship. More specifically, the lateral distance the ship has been forced off the desired path.
Leeway angle —See: *Drift, angle of.*
List —See: *Heel*
Long crested seas —A wave system in which all components advance in the same direction.
Lurch —A more or less isolated large roll amplitude.
Mass, added —See: *Added mass.*
Mass, added, coefficient —See: *Added mass coefficient*.
Moment, damping—A moment which tends to reduce the motion and, if assumed to be linear, is proportional to the angular velocity.
Moment, destabilising —A moment associated with a displacement from a position of equilibrium and tending to increase this displacement.
Moment, exciting —A fluctuating external moment that causes motion of a body or ship when encountering a train of waves.
Moments of inertia or roll, pitch and yaw moment of inertia (I_X ,I_{XX}, I_Y ,I_{YY}, I_Z ,I_{ZZ}) [L^2M] —The summation of products of elementary masses and the squares of their distances from the respective body axes through the centre of gravity – equal to the mass times the square of the *gyradius* or *radius of gyration* (which see). See General Section for body axes under *Axes, co-ordinate*.
Moment, pitching —Exciting moment in pitch.
Moment, restoring or righting —A moment tending to return a body to its initial condition after being displaced by an external moment.
Moment, rolling —Exciting moment in roll.
Moment, stabilising —Moment associated with a displacement from a position of equilibrium and tending to decrease this displacement.

Moment, wave bending, horizontal or lateral ($M^B{}_3$ or M_{L}, formerly M_{BH}) [L^{2}MT^{-2}] —That part of the inertial lateral bending moment acting on a cross section of a hull which is caused by the action of waves and ship motions.

Moment, wave bending, vertical ($M^B{}_2$ or M_{N} , formerly M_{BV}) [L^{2}MT^{-2}] —That part of the internal vertical bending moment acting on a cross section of a hull which is caused by the action of waves and ship motions.

Moment, wave, torsional (M^T or M_{T}) [L^{2}MT^{-2}] —That part of the internal torsional or twisting moment acting on a cross section of a hull which is caused by the action of waves and ship motions.

Motions, ship —The all-inclusive term to describe the various dynamic motions which may be made by a ship including the following which are defined separately:

i. *Rolling*, *Pitching* and *Yawing* (angular)

ii. *Heaving*, *Surging* and *Swaying* (translatory)

These motions may occur while the ship is stationary in the water or travelling through it.

Natural period of motions: heave, pitch, roll (T_{Z}, T_θ, T_φ) [T] —The time for one complete cycle of the motion resulting when a body or ship is displaced in calm water from its equilibrium position by an external force, then released.

Oscillator —A mechanism used to impose a controlled, known, oscillatory motion on a body. Also used to describe any oscillatory body.

Period (T) [T] —The time for one complete cycle of a periodic quantity or phenomenon. (See also: *Natural period of motions*).

Wave encounter period (T_{E}) [T] —The time between successive crests of a train of waves passing a fixed point in a ship, at a fixed angle of encounter μ; the reciprocal of the frequency of encounter f_{E} (which see).

Phase angle (ε_ι) [-]—The angle between two vector representing sinusoidal quantities of the same frequency.

Phase response operator —Phase angle between output and input of a linear system performing forced motion, as a function of frequency.

Pitch angle (θ) [-]—The angle, measured about the transverse body axis, between the instantaneous position of the longitudinal axis of a ship when *pitching* (which see) and its position of rest. (Positive bow up).

Pitching The angular component of the oscillatory motion of a hull about a transverse axis. Although pitching of a ship is a motion confined to operation in waves, it is possible with a high-speed planing craft for such motions to occur in calm water under some conditions. (See: *Porpoising*)

Porpoising —The cyclic oscillation of a high-speed craft primarily in calm water in which heaving motion is combined with pitching motion. The motion is sustained by energy drawn from the thrust.

Pounding —Described broadly as impacting between a water surface and the side or bottom of a hull. Pounding can perhaps be differentiated from slamming in that the impact, while heavy, is not in the nature of a shock. (See: *Slamming*)

Power in waves, mean increase in (P_{AW}) [L^{2}MT^{-3}] —The mean increase in power in wind and waves as compared with the water at the same mean speed.

Pressure, impact —A local pressure experienced by a hull when subjected to impact with the water. Usually associated with *slapping, slamming* or *pounding* (which see).

Radius of gyration —See: *Gyradius*.

Resistance in waves, mean increase in (R_{AW}) [LMT^{-2}] —The mean increase in resistance in wind and waves as compared with the still water resistance at the same speed.

Resonance —The dynamical condition of a simple, uncoupled system where the excitation frequency is equal to the natural frequency.

Note: In a coupled system, the dynamic condition where the excitation frequency corresponds to the frequency of maximum response to unit exciting force over a range of frequencies.

Response —The reaction of the system to an excitation.

Response amplitude operator —The square of the ratio of response amplitude to excitation amplitude of a forced harmonic motion applied to a linear system, as a function of frequency.

Response function —A complex function of which the modulus is equal to the response amplitude operator and the argument is equal to the phase response operator.

Revolutions, mean increase in rate of, in waves (n_{AW}) [Revs. T^{-1}] —The mean absolute increase in rate of revolution (usually per minute), as compared with those in smooth water, necessary to maintain speed in wind and waves.

Roll angle (ϕ) [-]—The angle measured about the longitudinal body axis, between the instantaneous position of a ship when *rolling* (which see) and its normal upright position. (Positive starboard down).

Rolling —The angular component of the oscillatory motion of a hull about a longitudinal axis.

Sea direction

Beam sea — A condition in which a ship and waves, or the predominant wave components, advance at right angles, or nearly so.

Bow sea — A condition in which a ship and the waves, or the predominant wave components, advance at oblique angles. This condition covers the direction between a head sea and beam sea.

Following sea — A condition in which ship and the waves, or predominant wave components, advance in the same, or nearly the same direction.

Head sea — A condition in which a ship and the waves, or the predominant components, advance in opposite, or nearly opposite directions.

Quartering sea — A condition in which a ship and the waves, or the predominant wave components, advance at oblique angles. This condition covers the directions between a beam sea and a following sea.

Seakeeping —In general, a term covering the study of the behaviour and performance of ship in a seaway. As an adjective, a term signifying a ship's ability to maintain normal functions at sea.

Seakindliness —The quality of behaving comfortably in a seaway; that property of ship which produces easy motions in a seaway.

Short-crested sea —An irregular wave system in which the components advance in various directions.

Sideslip, angle of —See: *Drift* or *sideslip, angle of.*

Significant wave height —See: *Wave height, significant*.

Sinkage —The steady state lowering of a ship's position of flotation in the water; to be distinguished from heaving, which is an oscillatory motion.

Slamming —A phenomenon described broadly as severe impacting between a water surface and the side or bottom of a hull where the impact causes a shock-like blow. (See also: *Pounding* and *Whipping*).

Slapping —A phenomenon described broadly as light impact between the water and the hull. A classification for impacts less severe than those associated with pounding. (See also: *Pounding*).

Smith effect —The difference between actual pressure at a point under a wave profile and the static pressure corresponding to the actual distance below the surface.

Spectral density, one dimensional ($S(\omega)$)—A function of frequency whose integral over any interval represent the energy contribution of all the component waves of a random function in that interval; the Fourier transform of the auto-covariance function.

$$S_{\zeta}(\omega)\mathrm{d}\omega = \sum_{\mathrm{d}\omega} \tfrac{1}{2}\zeta_{\mathrm{A}n}^{2}$$

$$S_{\theta}(\omega)\mathrm{d}\omega = \sum_{\mathrm{d}\omega} \tfrac{1}{2}\theta\zeta_{\mathrm{A}n}^{2}$$

etc.

The subscript n denotes a particular component amplitude.

Spectral density, two dimensional ($S(\omega,\mu)$)—A function of frequency and wave direction whose integral over any interval represents the energy contribution of all the component waves of a random function in that interval.

Spectrum

Amplitude — A function of frequency whose integral over any interval represents the squared amplitude of a wave at the central frequency having the same energy as all the component waves in that interval.

Co-spectrum — The real part of a *cross-spectrum* (which see).

Cross-spectrum — A complex function of frequency expressing the mutual properties of two random functions; the Fourier transform of the cross-covariance function, The real part, or co-spectrum, indicates the relationship between in-phase frequency components; the imaginary part, or quadrature spectrum, indicates the relation between 90° out-of-phase frequency components.

Quadrature spectrum — The imaginary part of a cross-spectrum.

Speed loss —The decrease in speed, as compared with that in smooth water, caused directly by wind and waves at a constant setting of the main propulsion plant. Usually speed loss is determined at constant power (turbine plant) or constant torque (diesel plant).

Speed reduction —The decrease in speed, as compared with that in smooth water, caused mainly by reducing the setting of the main propulsion plant in order to minimise the adverse effects ion the ship of wind and waves.

Springing —The continuous ship-hull vibration induced by the non-impulsive hydrodynamic forces acting on the ship hull. In particular, the vibratory response of the ship hull girder to short waves with frequencies of encounter close to the lower structural modes of vibration of the ship. See also: *Whipping*.

Stabiliser —Equipment to reduce the rolling (or pitching) motions of a ship.

Standard deviation—The square root of the average of the squares of the deviations from the mean value; the square root of the variance.

Steepness ratio, wave —See: *Wave steepness ratio*.

Stiffness —The property of a ship that causes a short rolling period.

Submergence () [L] —The relative vertical distance of a part (usually the bow) of an oscillating ship below the water surface; opposite to emergence.

Surging —The longitudinal oscillatory motion of a specified point in a ship, usually the centre of gravity (or origin of body axes).

Swaying —The transverse oscillatory motion of a specified point in the ship, usually the centre of gravity.

Thrust in waves, mean increase in (T_{AW}) [MLT^{-2}] —The mean increase in thrust, as compared with that in smooth water, necessary to maintain speed in wind and waves.

Torque in waves, mean increase in (Q_{AW}) [$\mathrm{ML}^{2}\mathrm{T}^{-2}$] —The mean increase in torque as compared with that in smooth water, necessary to maintain speed in wind and waves.

Transfer function —See: *Response function*.

Transient —Irregular or non-harmonic, such as the free vibration of a damped mechanical system.

Trim —The steady-state longitudinal angular position of a ship; to be distinguished from pitching, which is an oscillatory motion.

Trim, angle of (θ) [-]—The angle, measured about a horizontal axis, between the position of the longitudinal axis of a ship at rest and the horizontal plane.

Virtual mass —The combined effect of the mass of the ship and added mass corresponding to the hydrodynamic forces in phase with and proportional to the acceleration. (See also: *Added mass*.)

Wave —A disturbance of the surface of a fluid that usually progresses across the surface as the result of circular or other local motions of the fluid components. A standing wave is special case of a wave that does not advance.

Amplitude (ζ_A) [L] —The radius of orbital motion of a surface wave particle, equal to one half of the wave height.

Components — The infinity of infinitesimal waves of different frequencies and directions which are found by spectral analysis to compose an irregular sea, or the large of finite wave used to approximate such an irregular sea.

Direction, angle of (μ) [-] — The angle between the direction of a component wave and the x_0 axis.

Encounter, angle of (μ) [-] — The angle between the longitudinal axis of the ship and the direction of the wave encounter.

Encounter, period (T_E) [T] — The time between successive crests of a train of waves passing a fixed point in a ship, at a fixed angle of encounter μ; the reciprocal of the frequency of encounter f_E (which see).

Frequency (f) [T^{-1}] —The reciprocal of wave period = $1/T$, or circular frequency = $2\pi/T$.

Height (H_W) [L] — The vertical distance from wave crest to wave trough, or twice the wave amplitude of a harmonic wave.

Height, apparent (H_{WV}) [L] — The vertical distance between a successive crest and trough, estimated by visual observation.

Height, significant ($H_{W1/3}$) — The average apparent height of the 1/3 highest waves in an irregular pattern.

Instantaneous elevation (η) [L] — The instantaneous elevation of a point in a wave system above the level of the undisturbed surface.

Length (L_W, λ) [L] —The horizontal distance between adjacent wave crests in the direction of advance.

Length, apparent (L_{WV}) [L] — The horizontal distance between adjacent wave crests of an irregular sea in the direction of advance.

Number (κ) [L^{-1}] —

$$\kappa = \frac{2\pi}{\lambda} \quad \text{or} \quad \frac{2\pi}{L_W}$$

Period (T_W) [T] — The time between the passage of two successive wave crests passed a fixed point.

Period, apparent (T_{WV}) [T] — The time elapsing between the occurrence of two successive crests of an irregular sea, or between two successive upward crossing of zero in a record, estimated by visual observation.

Profile — The elevation of the surface particles of a wave plotted as a function of space in a fixed time.

Slope of surface — The surface slope of a wave profile perpendicular to the crest in space co-ordinate. Maximum wave slope of a regular harmonic or trochoidal wave is π/2 x steepness ratio.

Speed celerity (c_W) [LT^{-1}] — The phase velocity of a surface gravity wave in deep water.

$$c_W = \sqrt{\frac{gL_W}{2\pi}}$$

Steepness ratio — The ratio of wave height to length.

Train — A continuous sequence of wave crests and hollows.

Trochoidal — A profile closely approximating that of a regular surface gravity wave in a fluid; it can be geometrically constructed by tracing the path of a point on the radius of a circle as the circle rolls along the underside of a horizontal line.

Wetness —The quality of a part of the ship, usually the weather deck forward, with respect to its liability of being wet as a result of motions of ship and waves.

Whipping —The transient ship-hull vibration which is induced by impulsive excitation forces. For example, fore-bottom slamming, bow-flare slamming, shipping of water and stern slamming. (See also: *Springing*).

Yaw, angle (χ) [-]—The angle, measured about the vertical body axis, between the instantaneous position of the longitudinal centre plane of a ship when *yawing* (which see) and its mean heading. (Positive bow to starboard).

Yawing —The angular component of the oscillatory motion of a hull about a vertical axis.

7. MANOEUVRABILITY

In this section the term Manoeuvrability is used to define the quality which determines the ease with which the speed, attitude and direction of motion of a ship or body can be changed or maintained by its control devices.

Advance —The distance by which the centre of gravity (CG) of a ship advances in the first quadrant of a turn. It is measured parallel to the approach path, from the CG position at rudder execute to the CG position where the ship has changed heading by 90 degrees (See Figure 7-1). Maximum advance is the distance, measured parallel to the approach path from the CG position at rudder execute to the tangent to the path of the CG normal to the approach path. The first of these terms is that most commonly used.

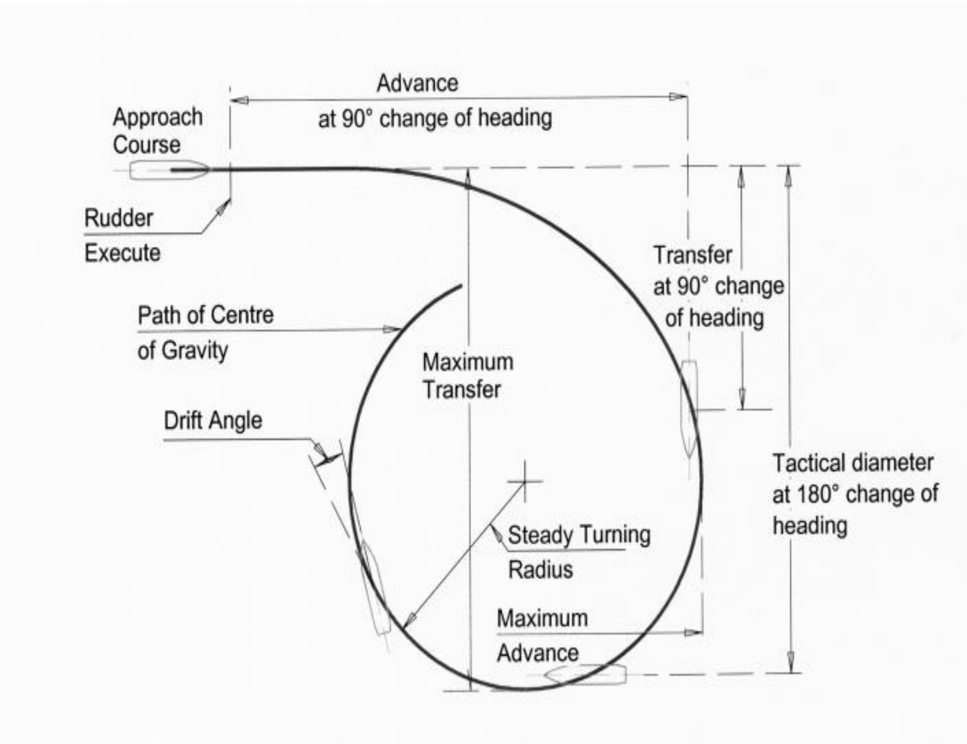


Figure 7-1: Geometry of turning circle.

Advance maximum (in stopping) — The distance travelled by a ship, in the direction of the approach path, before coming to rest after having executed a crash-back manoeuvre from a steady, straight-line motion ahead; it is also called *Headreach*. (See Figure 7-3). See also: *Transfer, maximum (in stopping).*

Angle of attack (α) [-]—The angle to the longitudinal body axis from the projection into the principal plane of symmetry of the velocity of the origin of the body axes relative to the fluid, positive in the positive sense of rotation about the y-axis. (See: *Axes, co-ordinate* in General Section).

Angle, control surface —See: *Control surface angle*.

Angle, downwash or sidewash —See: *Downwash or Sidewash angle*.

Angle of drift or sideslip —See: *Drift or sideslip, angle of*

Angle of heel or list —See: *Heel or list, angle*.

Angle of heel or roll, projected (or angle of attack in roll) (γ) [-]—The angular displacement about the x_0 axis of the principal plane of symmetry from the vertical, positive in the positive sense of rotation about the x_0 axis. (See: *Axes, co-ordinate* in General Section).

Angle, neutral —See: *Neutral angle*.

Angle, pitch —See: *Pitch angle*.

Angle, roll —See: *Roll angle.*

Angle, rudder —See: *Rudder angle* and *Rudder angle ordered*.

Angle, toe, of an offset rudder —The angle of a rudder, offset from the centreplane, when in its zero lift or neutral position, it does not lie parallel to that plane. The rudder "toes in" when its forward portion points inward toward the centreplane. To avoid ambiguity the terms "trailing edge out" or "trailing edge in" are often used.

Angle of trim —See: *Trim, angle of*.

Angle, vertical path or angle, flight path (θ_f) [-]—The vertical angle between the underwater path of the centre of gravity of a submerged body or submarine in motion and horizontal plane through that centre. The path angle is a combination of the trim angle and the angle of attack.

Angle, yaw See: —*Yaw angle.*

Approach speed —See: *Speed, approach.*

Area, control surface —See: *Control surface area*.

Area, lateral of the hull (A_{HL}, formerly A_L) [L^2] —The area of the profile of the underwater hull of a ship when projected normally upon the vertical, longitudinal centreline, including the area of skegs, deadwood, etc. Usually, areas which lie abreast of one another, such as those of multiple skegs, are included once only. Lateral area can refer not only to the whole body, but also to forebody, afterbody, entrance, run, etc. Thus A_{HLF}, A_{HLA}, A_{HLE}, A_{HLR}, etc.

Aspect ratio —See: *Ratio, aspect*.

Centre of lateral area —The centre of the lateral area of the immersed portion of a ship or body, taken generally in the plane of symmetry.

Centre of lateral force —The point in the plane of symmetry through which the resultant force would act to produce an effect equal to that of the total lateral hydrodynamic force on a vessel.

Coefficient of lateral area (C_{AL}, formerly C_{LA}) [-]—The ratio of the lateral area of the bare hull of a ship to the area of a rectangle having the ship length L and a constant depth equal to draft T_{X} at the station of maximum area.

Control devices —Control devices comprise all the various devices that are used to control a body or ship, such as control surfaces, thruster, jets, etc.

Control surfaces —Control surfaces are the rudders, hydroplanes and other hinged or movable devices used for controlling the motion of a body or ship.

Control surface angle (δ_{FB}, δ_{R} etc) [-]—The angular displacement of any control surface about its hinge or stock, such as that of a bow fin δ_{FB}, or rudder δ_{R}. Positive hen turning in the positive sense of rotation of the ship, regardless of the effect this angle may have on the ship. See also: *Rudder angle*.

Control surface area (A_{FB}, A_{FS}, A_{R}, etc) [L^2] —The plan form area of any active or movable control surface, such as that of bow fins A_{FB}, stern fins A_{FB} or rudder A_{R}, measured on the reference plane (generally the plane of symmetry). See also: *Rudder area*.

Course made good —The mean direction in which a ship is moving. This is defined by degrees of the compass or degree of azimuth in a horizontal plane. (See Figure 7-2).

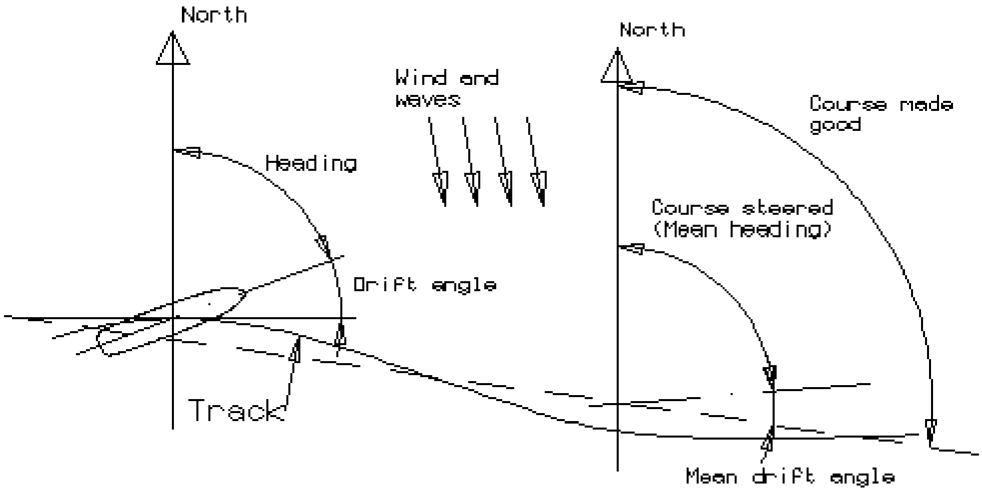


Figure 7-2: Course characteristics.

Course, steered (ψ_O) [-]—The mean heading of a ship, defined by degrees of the compass or degree of azimuth in a horizontal plane (See Figure 7-2).

Crash-back —A crash stop manoeuvre in which, while going ahead at normal or some other speed, the propulsion devices are reversed in the shortest possible time (See Figure 7-3).

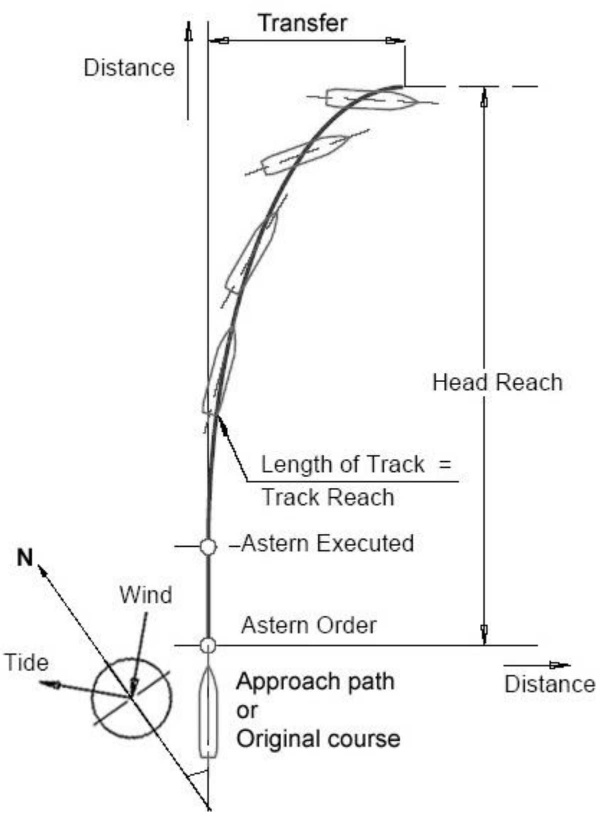


Figure 7-3: Crash back (stop) manoeuvre.

Cross force (C) —See: *Force, cross.*

Cross force coefficient (C_C) [-]—The ratio of the cross force C on a ship or body to the force corresponding to the dynamic pressure times a specified area. It is customary to expressed it as $C_C = C/qA$.

Deadwood —See: Ship geometry section.

Derivatives, stability and control —The hydrodynamic forces and moments which enter into the equations of motion are usually classified into three categories: static, rotary, and acceleration. The static derivatives are due to the components of linear velocity of the body relative to the fluid. Rotary derivatives are derived from angular velocity of the body and acceleration derivatives are from either linear or angular acceleration of the body.

Diameter, steady-turning —The diameter of the circular arc described by the centre of gravity of a ship when it has achieved a steady-turning state.

Diameter, tactical — (See Figure 7-1) The distance travelled by the centre of gravity of the ship normal to its original approach path in turning through 180 degrees. Tactical diameter is equal to the transfer at 180 degrees change of heading.

Directional stability —See: *Stability, directional*.

Downwash or sidewash —The deflection of a stream of fluid by any hydrofoil producing lift or thrust.

Downwash or Induced angle (α_{IND}, formerly ε) [-]—The angle of downwash (which see) measured in a plane through the nose-tail line of the hydrofoil and perpendicular to the hydrofoil axis.

Drag coefficient (C_D) [-]—A relationship between the drag D of a ship or body and the dynamic pressure times a specified area. It is customary to express it as $C_D = D/qA$. (See also: *Drag* and *Drag coefficient* in Resistance Section).

Drift —That motion, or component of motion, caused by some action other than that of the main propulsion devices of a ship, such as wind, waves, current and the like. See also: *Sideslip*.

Drift or sideslip, angle of (β) [-]—The horizontal angle between the instantaneous direction of motion of the centre of gravity of a ship and its longitudinal axis. It is positive in the positive sense of rotation about the vertical body axis.

Dynamic stability —See: *Stability dynamic*.

Edges, leading and trailing —The upstream and downstream edges, respectively, of a hydrofoil, propeller blade, rudder or similar device.

Fin —A fixed or movable hydrofoil, attached to a ship, generally in a longitudinal direction, to improve the dynamic stability or the manoeuvrability, or to provide a lift force to windward, as in the fin keel of a sailing yacht.

Force components, hydrodynamic (X, Y, Z) [LMT^{-2}] —The components of the total hydrodynamic force on a body or ship as resolved along its x-, y- and z-axes respectively. Related to the flow over the body, the components are the drag component, D or R, in the direction of the relative flow; the lift component, L, in the principal plane of symmetry normal to the relative flow; the cross force, C, on the body normal to lift and drag.

Force, cross (C) [LMT^{-2}] —A force exerted on a body, a hydrofoil, or a ship, with or without an angle of attack, at right angles to both the direction of lift and the direction of drag. Note: This is to be carefully distinguished from the lateral force; see: *Force, sway*.

Force, sway (Y) [LMT^{-2}] —The component of the total hydrodynamic force exerted by liquid on a body, acting perpendicular to the plane of symmetry. Specifically, the force developed on a ship, acting normal to the plane of symmetry, when the ship is caused to move sidewise in a horizontal plane, as in drifting, skidding or crabbing.

Heading (ψ) [] —The instantaneous direction of the projection of the forward longitudinal axis of a ship in a horizontal plane, defined by degrees of the compass or degrees azimuth. See also Figure 7-2.

Headreach —See: *Advance, maximum (in stopping)*.

Heel or list —A steady inclination of a ship about a longitudinal axis; to be distinguished from rolling, which is an oscillatory motion.

Heel or list, angle of (ϕ) [-]—The angle, measured about a longitudinal axis, between a static inclined position of a ship and its normal upright position.

Lift coefficient (C_L) [-]—A relationship between the lift force L developed by a ship or body and the dynamic pressure times a specified area. It is customary to express it as $C_L = L/qA$.

Manoeuvrability —Manoeuvrability is that quality which determinates the ease with which the speed, attitude and direction of motion of a body can be changed or maintained by its control devices.

Manoeuvring —The process of executing various voluntary evolutions with a ship, such as starting, stopping, backing, steering, turning, diving, rising, circling, zigzagging, dodging and the like.

Mass, added —See: *Seakeeping Section*.

Mass, added, coefficient —See: *Seakeeping Section*.

Moment, turning —A moment applied to a ship to cause it to assume angular dynamic motion about a vertical axis through the centre of gravity.

Moment, yaw (N) [L^2MT^{-2}] —A hydrodynamic moment due to environmental conditions acting on a ship which will tend to produce yawing in the form of an angular dynamic motion about the vertical or z-axis through the centre of the ship.

Neutral angle —The angle between any characteristic line or plane of a body or ship and any other intersecting line or plane taken as reference, when the forces, moments or other actions on or by the body or ship have a value of zero.

Overshoot —A state of motion of a body or liquid in which, following a disturbance of the equilibrium conditions, the body or liquid returns toward equilibrium and passes beyond it, because of kinetic energy stored up in the system as it passes through the equilibrium position (See Figure 7-4). See also: *Zigzagging*.

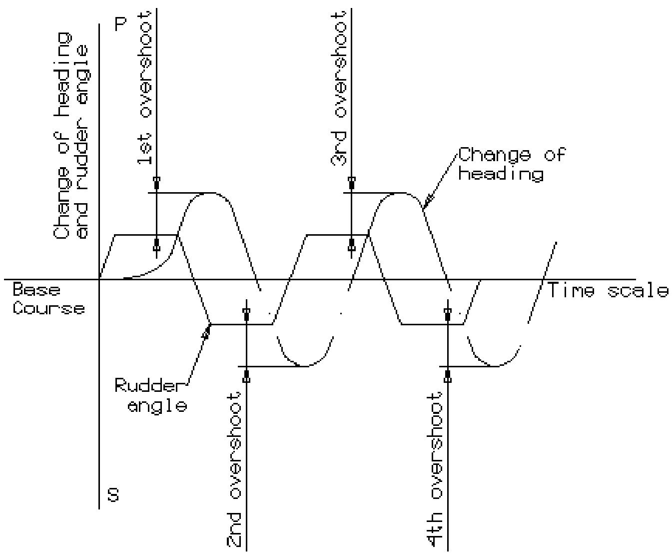


Figure 7-4: Zigzagging.

Pitch angle (θ) [-]—The angle, measured about the transverse body axis, between the instantaneous position of the longitudinal axis of a ship when pitching (which see) and its position of rest. (Positive bow up)

Pitching —The angular component of the oscillatory motion of a hull about a transverse axis. Although pitching of a ship is a motion confined to operation in waves, it is possible with a high speed planing craft for such motions to occur in calm under some conditions. (See: *Porpoising*)

Porpoising —The cyclic oscillation of a high-speed craft primarily in clam water in which heaving motion is combined with pitching motion. The motion is sustained by energy drawn from the thrust.

Positional motion stability —See: *Stability, course.*

Profile —The outline of a ship when projected on the fore-aft vertical centreline plane; also the outline of parts of the ship, such as the stem, stern, and rudder, when similarly projected. Note: This definition also covers the contour of any flat or curved surface which acts as a hydrofoil or as a control surface; examples are the profiles of diving planes on submarines, fitted generally in a horizontal plane, and the profile of the blades on a screw propeller.

Ratio, aspect (Λ)[-]—The ratio between the span of a hydrofoil, measured at right angles to the liquid flow, to the chord c of the hydrofoil, in the direction of flow. When the chord varies in length across the span, the aspect ratio is the span b divided by the mean chord c obtained generally dividing the hydrofoil projected area A_P into the square of the span b, i.e. b^2/A_P.

Roll angle (ϕ) [-] —The angle measured about the longitudinal body axis, between the instantaneous position of a ship when rolling (which see) and its normal upright position. (Positive starboard down).

Rolling —The angular component of the oscillatory motion of a hull about a longitudinal axis.

Rudder —A control surface, which by its action or movement, controls the steering or the turning of a ship in horizontal plane. Specifically, hinged or movable control-surface appendage in the form of a hydrofoil, placed either at the bow or at the stern of a ship, or at both ends, to apply a turning moment to the ship.

Rudder angle (δ_R) [-]—The angular displacement of the rudder about its stock relative to the neutral position and measured in a plane normal to the stock. Positive when turning in the positive sense of rotation of the ship, regardless of the effect this angle may have on the ship. See also: *Control surface angle*.

Rudder angle, ordered (δ_{RO}) [-]—The ordered angle set on the steering control apparatus. This may differ from the rudder angle δ_R, depending on the lag and lost motion in the steering control and gear.

Rudder area, total (A_R, A_{RT}) [L^2] —The total lateral area of the rudder (including fixed and movable parts) measured in the reference plane (generally the plane of symmetry). See also: *Control surface area*.

Rudder area, fixed (A_X) [L^2] —The lateral area of the sole fixed part of the rudder. See also: *Control surface area*.

Rudder area, movable (A_{Rmov}) [L^2] —The lateral area of the sole movable part of the rudder. See also: *Control surface area*.

Rudder directions—Right or starboard rudder signifies that the main portion of the rudder aft of the stock has moved to the right or to starboard of the centreline, to cause the ship to turn to the right or to starboard in forward motion. Similarly, left or port rudder signifies movement in the opposite direction.

Rudder post —A vertical or nearly vertical member of the ship's structure upon which the steering rudder is hung or supported.

Rudder span (b_R) [L] —The maximum distance from root to tip of the rudder. (See Figure 7-5).

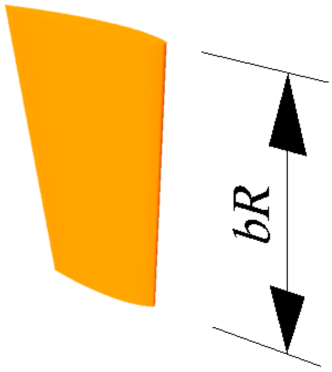


Figure 7-5: Rudder span.

Rudder stock —That portion of the rudder, concentric with the axis of rotation, which provides bearing support and also transmits the operating torque.

Rudder, thickness ratio —The ratio of the maximum thickness of any horizontal section of a rudder to the corresponding chord length.

Rudder types —See Figure

Balanced or semi-balanced: —A control surface in the form of a swinging rudder in which a small fraction of the area, generally about one-fifth, is placed forward of the vertical turning axis to reduce the operating torque in the ahead direction.

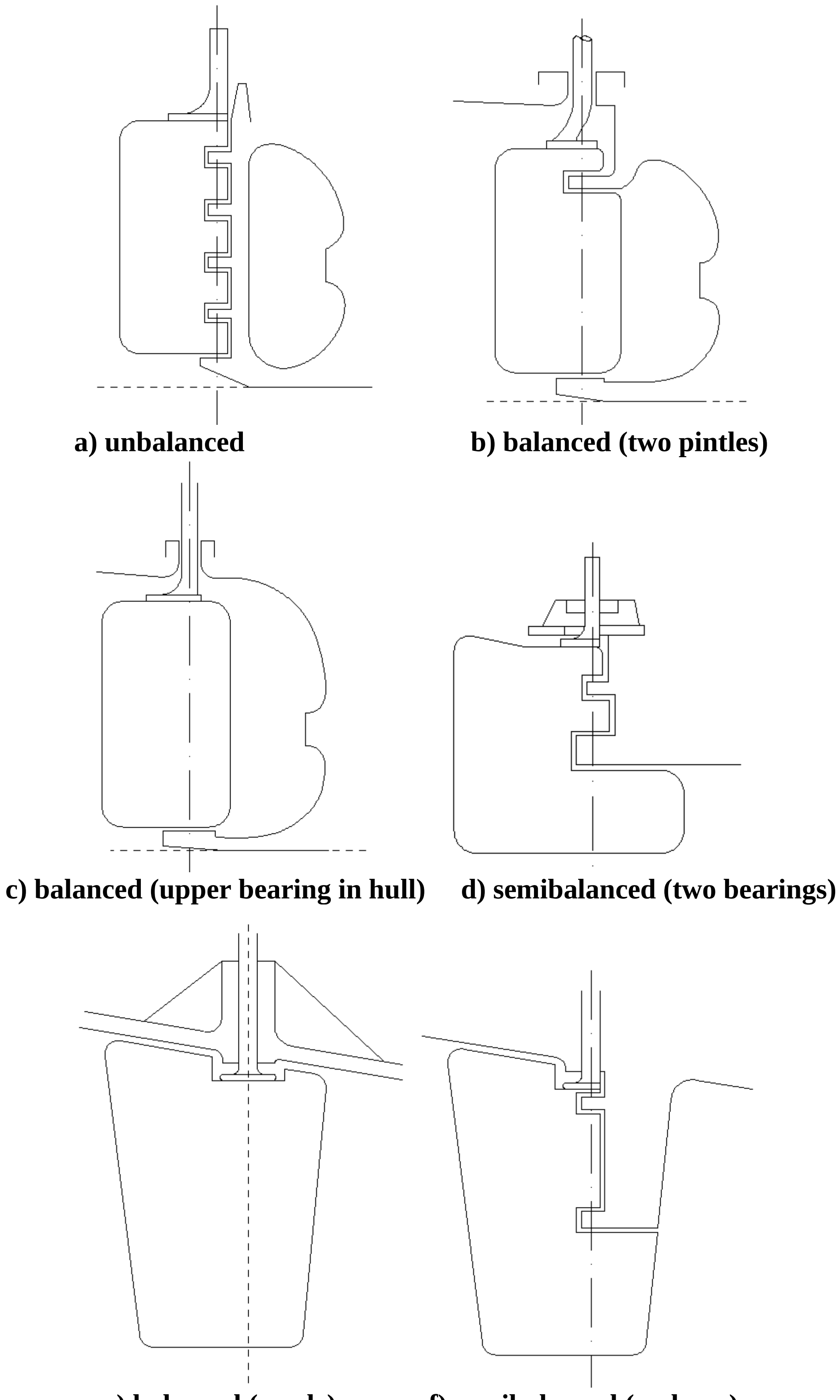
Compound: —A control device in the form of a fixed vertical appendage, to the after edge of which is hinged a movable or swinging rudder; see also: *Rudder, flap-type*.

Contra: —A rudder with a curved blade, designed to be mounted abaft a propeller to take advantage of the rotation in the slipstream and to produce a forward thrust on the rudder.

Flap: —A control device in the form of a moving rudder which is hinged for practically its entire vertical height to the hull, to a skeg, or to a fin which has an area large in proportion to that of the rudder. This type of rudder takes its name from the flaps on airplane wing; both function by building up large pressure differentials on the fixed parts of the ship or airplane to which they are attached.

Offset: —A rudder which is offset from the centreplane of a ship either to port or starboard.

Spade: —A control device in the form of a moving appendage which projects below the stern of the ship without any fixed supports in front of it or below it.



a) unbalanced **b) balanced (two pintles)**

c) balanced (upper bearing in hull) **d) semibalanced (two bearings)**

e) balanced (spade) **f) semibalanced (on horn)**

Figure 7-6: Rudder types.

Sideslip —The motion of a ship resulting from the propeller thrust, drag forces, hydrodynamic side forces on rudder and hull or centrifugal forces in a turn, may have a component at right angles to the vertical plane through the longitudinal axis of the ship. This is called the sideslip. See also: *Drift*.

Sideslip, angle of —See: *Drift or sideslip, angle of*.

Sidewash —See: *Downwash*

Skeg —A projection from or a fixed appendage applied to the underwater hull of a ship, generally to increase the lateral area and give increased swing damping and dynamic stability to the hull. A skeg is usually of large lateral area compared to its transverse thickness, is usually fitted in a vertical plane, and is in the after part of the vessel.

Speed, approach —The speed of a body or ship along the straight approach path, just prior to entry into a turn.

Spoiler —Any device ancillary to a hydrofoil or control surface or stabiliser to disturb the flow, in order to diminish the lift.

Stability, course —A body is said to have course stability if, when slightly disturbed from steady motion on a straight path, it returns to its original path, without any corrective control being applied. See Figure 7-7. Course stability in the horizontal plane does not normally exist, but a submarine can have it in the vertical plane. This is also known as *positional motion stability*.

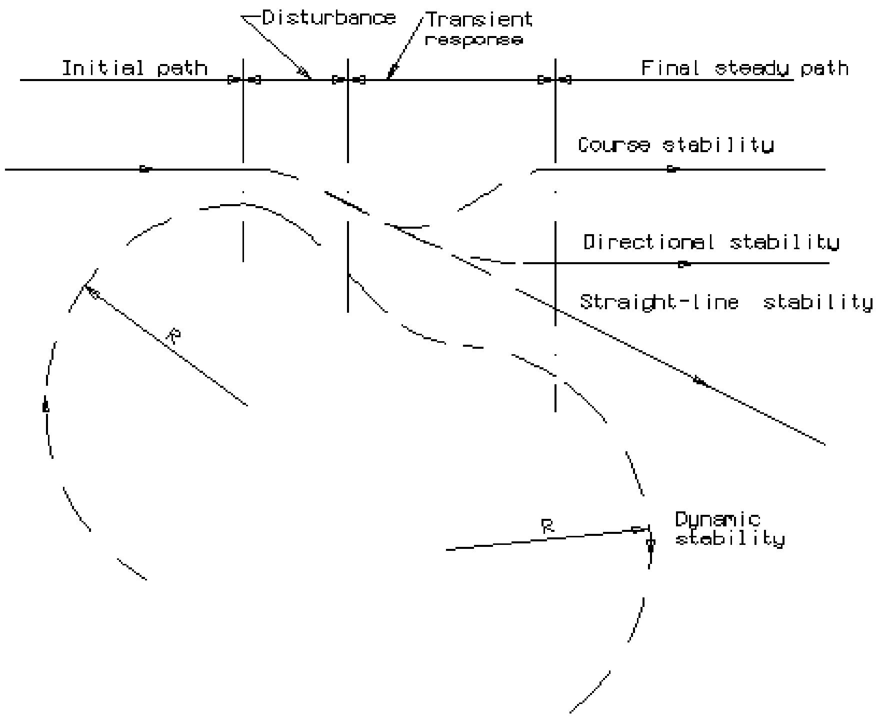


Figure 7-7: Illustration of stability items.

Stability, directional —A body is said to be a directionally stable if, when slightly disturbed from steady motion on a straight path, it returns to it original direction, but not necessarily its original path, without any corrective control being applied. See Figure 7-7. Directional stability in the horizontal plane does not exist, but a submarine can have it in the vertical plane. Note: The term directional stability is also commonly used to describe the more general case of straight-line stability (which see).

Stability, dynamic —A body is said to be dynamically stable on a straight course or on a turn constant curvature if, when slightly disturbed from a steady motion, it resume that same motion, but not necessarily along its original path, without any corrective control being applied. See Figure 7-7.

Stability, straight-line —A body is said to have straight-line stability if it is dynamically stable on a straight course. That is, when slightly disturbed from steady motion on a straight course, it resumes steady motion on a straight course, but not necessarily in its original direction, without any corrective control being applied. Figure 7-7.

Note: Straight-line stability is a special case of dynamic stability (which see); directional stability (which see) is a special case of straight-line stability; and course stability (which see) is a special case of directional stability.

Stability, weathercock —The directional or inherent stability of a body which is so restrained that its only freedom of motion is that of rotation about an axis perpendicular to the direction of relative liquid motion. The body tends to align itself with the direction of flow after being disturbed.

Note: In some quarters, as in wind tunnel establishments, this is also known as “static stability”.

Steering or course keeping —In its general sense, the guiding of vessel in a horizontal plane by a rudder on control device; specifically, keeping a vessel on, or as close as practicable to, a given or designated course, despite various disturbances. As distinguished from turning and manoeuvring, the term steering means keeping a vessel travelling in a given direction in a straight line.

Straight-line stability —See: *Stability, straight line*.

Swaying —The transverse oscillatory motion of a specified point in the ship, usually the centre of gravity.

Tab —A small auxiliary foil, movable or fixed, attached to a control surface such as a rudder or diving plane, generally at its after edge, to reduce the control force or moment by applying local differential pressure to the main control surface.

Toe angle of an offset rudder —See: *Angle, toe, of an offset rudder*.

Torque or moment, hinge or stock, of a control surface (Q_R, Q_{FB}, Q_{FS}, etc.) [L^2MT^{-2}] —The torque applied to the stock or actuating mechanism of a control surface by the hydrodynamic forces acting upon it. Also the torque applied to the control surface through the stock or actuating mechanism to change the position or attitude of that surface, e.g. rudder torque Q_R, bow fin torque Q_{FB}, stern fin torque Q_{FS}, etc.

Tow point —The point at which the towing force is applied on a ship which is towing or on a craft which is being towed.

Track —The path at which the centre of gravity of a ship is moving. See Figure 7-2.

Trail, trailing —As applied to a movable appendage or control surface, that condition in which the surface aligns itself with the surrounding flow, leading end foremost when all control force or moment is removed. An unbalanced rudder pivoted at its forward edge always trails when going ahead.

Transfer —The lateral offset of the CG of a body or ship in the first quadrant of turn, measured laterally from the extended approach path to the CG position when the body or ship has changed course 90 degrees. See Figure 7-1.

Transfer maximum (in stopping) —The lateral offset of the centre of gravity of a body or ship before coming to rest after having executed a crash-back manoeuvre from a steady, straight-line motion ahead. See Figure 7-3

Trim —The steady state longitudinal angular position of a ship; to be distinguished from pitching, which is an oscillatory motion.

Trim, angle of (θ) [-]—The angle, measured about a horizontal axis, between the position of the longitudinal axis of a ship at rest and the horizontal plane.

Turning —That phase of manoeuvring in which a body or ship while moving ahead or astern, changes course or direction. The beginning of a turn, starting with the initial deviation from the approach path, is known as the “entry” into the turn; the end of a turn terminating in a new straight course, is known as the “sortie”. See Figure 7-1.

Turning, steady —That phase of the turning in which the rate of change of heading steadies to a constant value.

Weathercock stability —See: *Stability, weathercock.*

Yaw, angle (χ) [-]—The angle, measured about the vertical body axis, between the instantaneous position of the longitudinal centreplane of a ship when *yawing* (which see) and its mean heading. (Positive bow to starboard).

Yawing —The angular component of the oscillatory motion of a hull about a vertical axis.

Zigzagging — A ship manoeuvre in which the course of a ship is deliberately changed at frequent intervals, as a deceptive or evasive manoeuvre, or as a trial manoeuvre, in accordance with a pre-determined or specified plan, while the average course made good remains approximately the same as if the ship were not zigzagging. See Figure 7-4.

8. PERFORMANCE

This Section is concerned essentially with performance in the context of power required to propel a ship at a given speed and various factors and matters related thereto. The propelling device is generally understood to be a screw propeller.

Admiralty coefficient —A quasi-dimensionless coefficient used for assessing or comparing the performance of ship.

$$\text{Admiralty coefficient} = \Delta^{\frac{2}{3}} V^3 / P,$$

where Δ is the displacement, V speed and P any corresponding power.

Advance, speed of —See: *Speed of advance*.

Air, still, resistance —See: *Resistance, wind*.

Angle, rudder —See: *Rudder angle* and *Rudder angle ordered*.

Apparent slip ratio —See: *Slip ratio, apparent*.

Appendage scale effect factor (β) [-]—A factor taking account of the effect of scale between model and ship on the resistance of appendages. It is defined by a factor β, where:

$$\frac{R_{\mathrm{APS}}}{1/2\,\rho_{\mathrm{S}} V_{\mathrm{S}}^2 S_{\mathrm{S}}} = \beta \frac{R_{\mathrm{APM}}}{1/2\,\rho_{\mathrm{M}} V_{\mathrm{M}}^2 S_{\mathrm{M}}}$$

Where R_{AP} is the appendage resistance (See: *Resistance, appendages*), ρ the fluid density, V the speed and S the wetted surface. The subscripts M and S mean tank and full-scale models, respectively.

Approach run —See: *Run, approach*.

Area, above-water projected —The area of the above-water hull, superstructure, deck erections, funnels, masts, and like, as projected onto either the vertical *x-z* or *y-z* plane of the ship. (See: *General Section* under *Axes, co-ordinate*).

Augment fraction, resistance —See: *Resistance augment fraction*.

Brake power —See: *Power, brake*.

Coefficient, Admiralty —See: *Admiralty coefficient*.

Coefficient, quasi-propulsive —See: *Efficiency, propulsive*, and *Efficiency, quasi-propulsive*.

Coefficient, wind resistance —See: *Resistance coefficient, wind*.

Correlation allowance, model-ship (R_{A}) [LMT^{-2}] —This is the addition which has to be made to the resistance of the "smooth" ship, as predicted from the model results, to bring it into agreement with the actual ship performance determined from full scale trial or service result. The correlation allowance depends upon the method used to extrapolate the model results to the "smooth" ship, the ship length and type, the basic shell roughness of the newly painted ship, fouling, weather conditions at the time the ship measurements were taken and scale effects on the factor making up the model and ship propulsive coefficients.

Correlation allowance coefficient —See: *Resistance coefficient, incremental, for model-ship correlation*.

Correlation factor, ship-model, for propeller rate of evolution (K_2) [-]—The scale effect between the rate of propeller rotation of model n_{M} and ship n_{S} is defined by the factor K_2, such that

$$K_2 = \frac{n_{\mathrm{S}}}{n_{\mathrm{M}}} \sqrt{\lambda}$$

where λ is the scale factor.

Correlation factor, ship-model, for propulsive or quasi-propulsive efficiency (K_1) [-] —The scale effect between the propulsive efficiencies of the model and ship is defined by the factor K_1, such that

$$K_1 = \frac{\eta_{\mathrm{DS}}}{\eta_{\mathrm{DM}}}$$

where the efficiencies η_{DS} and η_{DM} for ship and model respectively are derived at corresponding speed and propeller loading.

Course made good —The mean direction that a ship is moving. This is defined by degrees of the compass or degrees of azimuth in a horizontal plane. (See Figure 7-2).

Course measured —A straight measured course, which is used for speed trials of a ship. When such a course is one nautical mile in length it is often referred to as a measured mile.

Course steered () [-]—The mean heading of a ship, defined by degrees of the compass or degrees of azimuth in a horizontal plane. (See Figure 7-2).

Course, original (ψ_0) [-]—The course at the beginning of a manoeuvring test, defined by degrees of the compass or degree of azimuth in a horizontal plane (See Figure 7-1 and Figure 7-3).

Current, tidal —A current in the water caused by the tide and influenced by the coastline and contours of the seabed.

Current, wind —A surface or near-surface current in a body of water induced by wind.

Delivered power —See: *Power, delivered*.

Effective power —See: *Power, effective*.

Effective wake fraction—See: *Wake fraction, effective*.

Efficiency, gearing (η_{G}) [-]—The ratio of the power output to the power input of a set of reduction – or multiplying – gears between an engine and propulsion device:

$$\eta_G = \frac{P_S}{P_B}$$

where P_{S} and P_{B} are the shaft and brake powers respectively (which see).

Efficiency, hull (η_{H}) [-]—The ratio between the useful work done on the ship and the work done by the propeller or other propulsion devices in a given time that is effective power P_{E} and thrust power P_{T} respectively.

$$\eta_{\mathrm{H}} = \frac{P_{\mathrm{E}}}{P_{\mathrm{T}}} = \frac{R_{\mathrm{T}}V}{TV_{\mathrm{A}}} = \frac{1-t}{1-w} \text{ in Taylor notation}$$

or

$$\eta_H = (1 + w_{\mathrm{F}})(1 - t) \text{ in Froude notation}$$

Where R_{T} is the total resistance, V the ship speed, T the propeller thrust and V_{A} the speed of advance; t is the thrust deduction fraction; w and w_{F} are the wake fractions according to Taylor and Froude respectively (which see).

Efficiency, mechanical (η_{M}) [-]—The ratio between the power output and the power input of any machinery installation.

$$\eta_{\mathrm{M}} = \frac{P_{\mathrm{S}}}{P_{\mathrm{I}}}$$

or

$$\eta_{\mathrm{M}} = \frac{P_{\mathrm{B}}}{P_{\mathrm{I}}}$$

where P_{S} and P_{B} are the shaft and brake powers respectively and P_{I} is the indicted power (which see).

Efficiency, propeller, behind hull (η_B) [-]—The ratio between the power P_T, developed by the thrust of the propeller and the power P_D absorbed by the propeller when operating behind a model or ship:

$$\eta_B = \frac{P_T}{P_D} = \frac{TV_A}{2\pi Qn} = \eta_0 \eta_R$$

where T is the thrust, V_A speed of advance, Q shaft torque and n rate of propeller rotation; η_0 and η_R are the open water propeller and relative rotative efficiencies respectively.

Efficiency propeller, open water (η_O) [-]—The ratio between the power developed by the thrust of the propeller P_T, and the power absorbed by the propeller P_D when operating in open water with uniform inflow velocity V_A:

$$\eta_0 = \frac{P_T}{P_D} = \frac{TV_A}{2\pi Q_0 n}$$

where T is the thrust, Q_0 the torque in open water and n the rate of propeller rotation.

Efficiency, quasi-propulsive or quasi-propulsive coefficient (η_D) [-]—The ratio between the useful or effective power P_E and the power delivered to the propeller or the propulsion device P_D.

$$\eta_D = \frac{P_E}{P_D} = \eta_0 \eta_H \eta_R$$

where η_O, η_H and η_R are the open water propeller, hull and relative rotative efficiencies respectively (which see).

Efficiency, propulsive (η_P) [-]—The ratio between the useful or effective power P_E and the brake power P_B.

$$\eta_P = \frac{P_E}{P_B} = \eta_0 \eta_H \eta_R \eta_S \eta_G$$

where η_0, η_H η_R η_S and η_G are the open water propeller, hull relative rotative shafting and gearing efficiencies respectively (which see).

Efficiency, relative rotative (η_R) [-]—The relative rotative efficiency is the ratio of the propeller efficiencies behind the hull and in open water, as already defined.

$$\eta_R = \frac{\eta_B}{\eta_0}$$

Efficiency, shafting (η_S) [-]—The shafting efficiency is a measure of the power lost in shaft bearings and stern tube:

$$\eta_S = \frac{P_D}{P_S}$$

where P_D and P_S are the delivered and shaft powers respectively (which see).

Factor, appendage scale effect —See: *Appendage scale effect factor*.

Factor, form —See: *Form factor*.

Factor, load —See: *Power prediction factor*.

Factor, ship-model correlation —See: *Correlation factor*.

Friction deduction force in self propulsion test (F_D) [LMT^{-2}] —The towing force applied to a model to compensate for the increased specific frictional resistance of the model and to achieve the ship-point of self-propulsion.

Form effect —The difference between the viscous resistance of a model or a ship and the two dimensional friction resistance of a flat plate of the same length and wetted area and at the same speed in a given fluid. The difference arises because of the augmented speed of flow around the ship form as compared with along a flat plate and the pressure resistance of viscous origin. See also: *Form factor*.

Form factor (k) [-]—The ratio between the total viscous resistance coefficient of a model or a ship C_{V} and the two dimensional frictional resistance coefficient of a flat place C_{F0} or C_F at the same free stream Reynolds number. It may be expressed in two ways, either:

$$k = \frac{C_V - C_{F0}}{C_{F0}}$$

or

$$k = \frac{C_V - C_F}{C_F}$$

Fraction overload —See: *Power prediction factor*.

Fraction, resistance augment —See: *Resistance augment fraction*.

Fraction, thrust deduction —See: *Thrust deduction fraction*.

Fraction, wake —See: *Wake fraction*.

Fresh water, standard —See: *Water, standard fresh*.

Frictional wake —See: *Wake, frictional*.

Gearing efficiency —See: *Efficiency, gearing*.

Geosim —One of a series of models which differ in absolute size but are geometrically similar. It is a contraction of the expression "geometrically similar model" and was first used by Dr. E. V. Telfer.

Ground speed —See: *Speed, ground*.

Heading (ψ) [] —The instantaneous direction of the projection of the forward longitudinal axis of a ship in a horizontal plane, defined by degrees of the compass or degrees azimuth. See also Figure 7-2.

Hull efficiency —See: *Efficiency, hull*.

Hydraulically smooth surface —See: *Surface, smooth*.

Indicated power —See: *Power, indicated*.

Load factor ($1+x$) [-]—See: *Power prediction factor*.

Load fraction in power prediction (x) [-]—

$$x = \eta_{\mathrm{D}} \frac{P_{\mathrm{D}}}{P_{\mathrm{E}}} - 1$$

where P_{D} and P_{E} are the delivered and effective powers respectively and η_{D} the quasi-propulsive efficiency (which see).
See also: *Power prediction factor*.

Measured course —See: *Course, measured*.

Mechanical efficiency —See: *Efficiency, mechanical*.

Mile, measured. —See: *Course measured*.

Overload fraction —See: *Power prediction factor*.

Potential wake —See: *Wake, potential*.

Power, brake (P_{B}) [$\mathrm{L}^2\mathrm{MT}^{-3}$] —The power measured at the engine coupling by means of mechanical, hydraulic or electrical brake.

Power, delivered (P_{D}) [$\mathrm{L}^2\mathrm{MT}^{-3}$] — The power delivered to the propeller:

$$P_{\mathrm{D}} = 2\pi n Q$$

Power, effective (P_E) [L^2MT^{-3}] — The power required to tow a ship, usually without its propulsive device, at constant speed V in unlimited undisturbed water:

$$P_E = R_T V$$

The power may be for ship either with or without appendages. If the latter, it is usually known as the naked or bare hull, effective power.

Power, indicated (P_I) [L^2MT^{-3}] —The power developed in the cylinders of a reciprocating engine, either steam or diesel, as determined from the pressure measured by an indicator or similar device.

Power prediction factor ($1+x$) [-]—A factor based on the correlation of ship and corresponding model data, which is introduced in estimating ship power to allow for the method of extrapolating model results to ship, scale effects on resistance and propulsion and the effects of hull roughness and weather conditions such that:

$$P_D = \frac{P_E(1+x)}{\eta_D}$$

where P_D and P_E are the delivered and effective powers respectively and η_D the quasi-propulsive efficiency (which see).

The results of model propulsion experiments are analysed for a propeller loading equivalent to the power prediction factor. The factor ($1+x$) is sometimes known as the *load factor* and the factor x as the *load fraction* (which see).

Power, shaft (P_S) [L^2MT^{-3}] —The power delivered to the shafting system by the propelling machinery.

Power, thrust (P_T) [L^2MT^{-3}] —The power developed by the propeller thrust T, at the speed of advance V_A:

$$P_T = TV_A$$

Power in waves, mean increase in (P_{AW}) [L^2MT^{-3}] —The mean increase in power in wind and waves as compared with the power in still water at the same mean speed.

Propeller efficiency —See: *Efficiency, propeller*.

Propulsive coefficient or efficiency —See: *Efficiency, propulsive*.

Quasi-propulsive coefficient or efficiency —See: *Efficiency, propulsive*.

Ratio, slip —See: *Slip ratio*.

Relative rotative efficiency —See: *Efficiency, relative rotative*.

Relative wind —See: *Wind, relative*.

Resistance, appendages (R_{AP}) [LMT^{-2}] —The increase in resistance relative to that of the naked, or bare hull resistance, caused by appendages such as bilge keels, rudders, bossings, struts, etc.

Resistance augment fraction (a) [-]—The thrust T required to propel a model or ship at speed V is greater than the resistance R_T of the hull when towed at the same speed. The increase $(T - R_T)$ is called the augment of resistance, and the resistance augment fraction is:

$$a = \frac{T - R_T}{R_T}$$

$$T = (1 + a)R_T$$

Resistance coefficient, incremental, for model-ship correlation (C_A) [-]—The model-ship correlation allowance R_A (which see) expressed in coefficient form:

$$C_A = \frac{R_A}{\frac{1}{2}\rho V^2 S}$$

where ρ is the water density, V speed and S wetted surface.

Resistance coefficient, wind (C_{AA}) [-]—The ratio between the air or wind resistance on a ship or body R_{AA}, and the force corresponding to the dynamic pressure times a specified area. It is customary to expressed it as:

$$C_{\mathrm{AA}} = \frac{R_{\mathrm{AA}}}{\frac{1}{2}\rho V_R^2 S}$$

where A is the appropriate above water area of the ship, V_R the relative wind velocity (which see) and ρ the air density.

Resistance, roughness (R_{AR}) [LMT^{-2}] —The increase in resistance relative to the resistance of a hydraulically smooth hull due to the effect of roughness. The hull roughness may be of different types such as:

Structural roughness caused by method of shell construction, waviness of plating, scoops, valve openings etc.

Paint roughness depends on the type of paint as well as how it is applied.

Corrosion roughness is caused by breakdown of the paint film and corrosion of the shell plating.

Fouling roughness is caused by marine organisms depositing shell, grass etc.

Resistance, still air —See: *Resistance, wind.*

Resistance in waves, mean increase in (R_{AW}) [LMT^{-2}] —The mean increase in resistance in wind and waves as compared with the still water resistance at the same mean speed.

Resistance, wind (R_{AA}) [LMT^{-2}] —The fore and aft component of the resistance of above water form of a ship due to its motion relative to still air or wind. When there is no natural wind, this is called the still air resistance. See also: *Resistance coefficient, wind.*

Restricted water —See: *Water, restricted.*

Revolutions, rate of, mean in waves (n_{AW}) [T^{-1}] —The mean absolute increase in rate of revolutions (usually per minute), as compared with those in smooth water, necessary to maintain speed in wind and waves.

Rough surface —See: *Surface, rough.*

Roughness allowance (ΔC_F) [-]—Now obsolescent, See: *Resistance coefficient, incremental for model-ship correlation* (C_A)

Roughness, equivalent sand (K_S) [L] —Equivalent sand roughness is used as a convenient measure of the roughness of a surface and is determined by equating the frictional resistance of a surface of random roughness with that of a flat plate completely covered with sand grains of a sensibly uniform size as in Nikuradse’s experiments. It is the average diameter of the Nikuradse sand grains.

Roughness, height or magnitude (k) [L] A length dimension expressing the height of a roughness element on a surface exposed to liquid flow. It is often expressed as some form of average such as root mean square or mean apparent amplitude.

Roughness, resistance —See: *Resistance, roughness.*

Rudder angle (δ_R) [-]—The angular displacement of a rudder about its stock relative to the neutral position and measured in a plane normal to the stock. See also: *Manoeuvrability Section.*

Rudder angle, ordered (δ_{RO}) [-]—The ordered angle set on the steering control apparatus. This may differ from the rudder angle δ_R, depending on the lag and lost motion in the steering control and gear.

Run approach —The path taken by a ship when accelerating during the approach to a measured course to attain a steady speed corresponding to give engine setting.

Salt water, standard —See: *Water, standard salt.*

Scale effect —The change in any force, moment or pressure coefficients, flow pattern, or the like, due to a change in absolute size between geometrically similar models, bodies or ships. These variations in performance due to differences in absolute size arise from the inability to satisfy simultaneously all the relevant laws of dynamical similarity (e.g. gravitational, viscous and surface tension).

Shaft power —See: *Power, shaft*.

Shafting efficiency —See: *Efficiency, shafting*.

Shallow water —See: *Water, shallow*.

Slip ratio, apparent (s_A) [-]—This is similar to the real slip ratio (which see) except that the ship speed V is used instead of the speed of advance V_A, that is:

$$s_A = \frac{Pn - V}{Pn} = 1 - \frac{V}{Pn}$$

Slip ratio, real (s_R) [-]—This is defined by the ratio:

$$s_R = \frac{Pn - V_A}{Pn} = 1 - \frac{V_A}{Pn}$$

where P is the nominal, geometrical pitch, or the effective pitch of the propeller (i.e. advance per revolution at zero thrust), V_A is the speed of advance and n the rate of propeller rotation.

Smooth surface See: *Surface, smooth*.

Speed of advance of a propeller (V_A) [LT^{-1}] —Speed of advance of a propeller in open water. When a propeller behind a ship or model is producing the same thrust at the same rate of rotation as in open water the corresponding speed V_A determined from the open water propeller characteristic is termed the speed of advance of the propeller. This is usually less than the ship speed V. (See also: *Wake fraction, effective*). This is based on thrust identity. There is another corresponding speed based on torque identity.

Speed, corresponding —The speed of a ship V_S related to that of a model V_M, or vice-versa, according to Froude's Law of comparison:

$$V_S = V_M\sqrt{\lambda}$$

where λ is the scale factor.

Speed, ground —The speed of a ship relative to the ground, that is the speed including the effects of tide and currents. When the ship is moving through still water the ground speed is the same as the true water speed.

Speed loss —The decrease in speed, as compared with that in smooth water, caused directly by wind and waves at a constant setting of the main propulsion plant. Usually speed loss is determined at constant power (turbine plant) or constant torque (diesel plant).

Speed reduction —The decrease in speed, as compared with that in smooth water, caused mainly by reducing the setting of the main propulsion plant in order to minimise the adverse effects on the ship of wind and waves.

Speed, true water —The speed of a ship relative to the surrounding water.

Still air resistance —See: *Resistance, wind*.

Surface, rough —A surface marked by sensible or visible irregularities.

Surface, smooth —A surface free from irregularities sensible to the touch or visible to the naked eye. A surface is called hydraulically smooth when there is no increase of resistance due to the surface irregularities.

Surface, wavy —A surface, which may be either smooth or rough, in which there are undulations of relatively large curvature.

Thrust deduction factor (t) [-]—It is logical to view the effect of the propeller behind the hull as causing an increase in resistance- See: *Resistance augment fraction*. However, it is also common practice to look upon this increase in R_T as a deduction from the thrust T available at the propeller, i.e. to assume that of the total thrust T only R_T is available to overcome resistance. This "loss of thrust" $(T - R_T)$, expressed as a fraction of the thrust T, is called the thrust deduction fraction, t, where

$$t = \frac{T - R_T}{T}$$

or

$$R_T = (1 - t)T$$

Thrust power —See: *Power, thrust*.

Towing force, for model at ship-point of self-propulsion —See: *Force, model towing*.

Track —The path along which the centre of gravity of a ship is moving (See Figure 7-2).

Trial, measured mile —A trial carried out on a measured mile course to determinate the performance characteristics of a ship, namely ship speed, corresponding rate of rotation of propeller shaft, power, and also thrust where practicable.

True wind direction or velocity —See: *wind direction or velocity, true*.

Wake —The wake is a term used to describe the motion imparted to the water by the passage of the ship's hull. It is considered to be positive if its direction is the same as that of the ship.

Wake fraction (w, w_F) [-]—The difference between the ship speed V and the speed of advance V_A is called the wake speed $(V - V_A)$. Froude expressed the wake speed at the position of the propeller as a fraction of the speed of advance, calling this ratio the wake fraction w_F, such that

$$w_F = \frac{V - V_A}{V_A} \text{ and } V_A = \frac{V}{1 + w_F}$$

Taylor expressed the wake speed at the position of the propeller as a fraction of the ship speed, such that

$$w = \frac{V - V_A}{V} \text{ and } V_A = V(1 - w).$$

Wake fraction, torque (w_Q) [-]—A propeller will develop the same torque Q at the same revolutions per unit time, n, when working behind a hull advancing at speed V and in open water at a speed of advance V_A. The torque wake fraction will then be

$$w_Q = \frac{V - V_A}{V}$$

This depends on identity of torque.

Wake fraction, thrust (w_T) [-]—A propeller will develop the same thrust T at the same revolutions per unit time, n, when working behind a hull advancing at speed V and in open water at a speed of advance V_A. The thrust wake fraction will then be

$$w_T = \frac{V - V_A}{V}$$

This depends on identity of thrust.

Wake fraction, nominal [-]—Wake fractions calculated from speed measured at the propeller position by Pitot tube, vane wheels, etc. in the absence of the propeller are called nominal wakes.

Wake, frictional —The component of the wake which results from the frictional action of the water when moving along the solid surface of a body or ship.

Wake, potential —The component of the wake due to the potential flow around a body or ship, with velocity and pressure relationship in accordance with Bernoulli's Theorem.

Wake, wave or orbital —The component of the wake set up by the orbital motion in the waves created by a body or ship.

Water, restricted —A term describing a body of water in which the boundaries are close enough to the ship to affect its resistance, speed, attitude, manoeuvring, and other performance characteristics, as compared with the corresponding characteristics in an open, unlimited, body of water. Principally, "restricted" applies to the proximity of the water boundaries in a horizontal direction.

Water, shallow —A term describing a body of water in which the boundaries are closed enough to the ship in a vertical direction to affect its resistance, speed, attitude, manoeuvring, or other performance characteristics as compared with its corresponding characteristics in water of unlimited depth.

Water, standard fresh —Water having zero salinity and a temperature of 15°C (59°F) with: density ρ = 999.00 kg/m^3 (1.9384 lb s^2/ft^4.)
Kinematic viscosity ν = 1.13902 * 10^{-6} m^2/s. (1.22603 10^{-5} ft^2/s)*

Water, standard salt —Water having 3.5 per cent salinity and a temperature of 15°C (59°F) with: density ρ = 1,02587 Kg/m^3 (1.9905 lb s^2/ft^4)
Kinematic viscosity ν = 1.18831*10^{-6} m^2/s. (1.27908*10^{-5}ft^2/s)*
*See also relevant items in General Section under "Liquid Properties and Physical Constants".

Wavy surface —See: *Surface, wavy*.

Wind, angle apparent (β_{AW}) [-]—The direction of the relative wind with respect to a ship's heading. The resultant direction of the wind induced by the ship's motion and the true wind, if any.

Wind, angle true (β_{TW}) [-]—The direction of the wind, if any, with respect to a ship's heading.

Wind direction (θ_W) [-]—The direction of any natural or atmospheric wind blowing over the ground or over the surface of the sea, measured from the true North.

Wind resistance —See: *Resistance wind*.

Wind velocity, relative (V_{WR}) [LT^{-1}] —The velocity of the true wind relative to the ship. It is the resultant of the wind induced by the ship's motion and the true wind, if any.

Wind velocity, true (V_{WT}) [LT^{-1}] —The velocity of air relative to the ground.

Yaw, angle (χ) [-]—The angle, measured about the vertical body axis, between the instantaneous position of the longitudinal centreplane of a ship when *yawing* (which see) and its mean heading. (Positive bow to starboard).

9. OFFSHORE ENGINEERING

7. General

Drill Ship — A ship specially equipped to conduct drilling of oil wells at sea (See Figure 9-1). The primary difference between a drill ship and conventional vessel is the presence of a centre opening (moonpool) for conducting drilling operations. The principal requirement for the propulsion system of a drillship is the ability to hold the vessel at a fixed position over the drill hole, since in deeper water anchors cannot be used. Compared to cargo vessels, drill ships are designed to remain at sea for long periods, and the consequences of component or system failure are far greater than for most conventional ships.

Figure 9-1: A typical modern Drill Ship with dual heads.

Drilling unit, Jack-up — A Jack-up is a self-elevating offshore drilling unit that consists of a self-floating, flat box-type deck structure supporting the drilling rig, drilling equipment and accommodation (See Figure 9-2). It stands on 3 or 4 vertical legs along which the platform can be self-elevated out of the water to a sufficient height to remain clear of the highest waves. Drilling operations take place in the elevated condition with the platform standing on the seabed. This type of drilling unit is used for drilling operations in water depths up to about 100 m. Jack-ups spend part of their life as floating structures. This is when such units are towed to a new location by means of oceangoing tugs. In this mode, the legs are lifted up and extend upwards over the platform. The Jack-up-type mobile offshore drilling unit (MODU) has become the premier bottom-founded drilling unit, displacing submersibles and most platform units.

The primary advantage of the Jack-up design is that it offers a steady and relatively motion-free platform in the drilling position and mobilizes relatively quickly and easily. Although they originally were designed to operate in very shallow water, some newer units are huge and can be operated in 170 m of water in the Gulf of Mexico (GOM).

Figure 9-2: Jack-up Drilling Unit.

Drilling unit, Mobile Offshore — Mobile offshore drilling units (MODU) are vessels (self-propelled or not) capable of engaging in drilling operations for the exploration or for exploitation of resources beneath the seabed such as liquid or gaseous hydrocarbons, sulphur or salt. (SOLAS IX/1, MODU Code 2009 paragraph 1.3.40).

Drilling unit, Semisubmersible —A semisubmersible drilling unit is a column-stabilized vessel consisting of a main deck (Topside Deck Structure) connected to the underwater hulls or pontoons by columns or caissons (See Figure 9-3). The weight of the columns is high and without sufficient buoyancy in and of themselves to float the platform. Pontoons are provided at the bottom of the columns for additional buoyancy and the most common arrangement is either twin pontoons connected by braces or a ring (continuous) pontoon. Drilling equipment, mud systems, living quarters and so forth are placed on the main deck, and ballast tanks, thrusters, sea water pumps are arranged in the underwater hulls. These units can work in very shallow water depths, less than 30 m in some cases, to the deepest water depths, 3,000 m or more.
Sometimes referred to as a "column-stabilized" vessel, the semisubmersible's combination of hull mass and its displacement, the wave transparency of the hull because of the columns, and its deep draft enable waves to pass through the unit with minimal energy exciting it to excessive roll, pitch, sway, surge, heave, and yaw. With the work deck above the wave crests, this design is a very capable work platform in severe environments. As with Jack-ups, the air gap is critical and is a

major design consideration when the unit is rated for environmental conditions. During the design of a semi-submersible, hull motion analysis in relation to waves crashing into the upper deck is critical. Under no circumstance should a MODU be designed or rated for environmental conditions in which waves will come in contact with the upper hull. In addition, heave, roll, pitch, sway, yaw, and surge need to be analysed in terms of the upper limits of motion in which crews and equipment can operate.

For example, significant amounts of heave, if slow (long periods), may be tolerable for most operations; however, short heaves with very short periods are more challenging. From a crew performance standpoint, smooth predictable motions generally do not hinder performance; however, jerky unpredictable motion will have a significant negative impact. Metocean conditions throughout the world result in most semi-submersibles being operated in less than 8- to 10-s wave or swell periods, so motions below these periods are usually not of concern. A swell period of interest is the "resonance" or natural period in which the hull motion actually exceeds the environmental value (> 1.0 ratio) for motion (i.e., the hull heave is more than the wave height). It is generally agreed for semi-submersibles designs that the resonance period for heave should be more than 17–18 s in the Gulf of Mexico (GOM) to prevent resonance. The resonance period varies in other areas.

Figure 9-3: Semisubmersible Drilling Unit.

Drilling unit, Submersible — A submersible unit is a particular type of floating vessel, usually used as a mobile offshore drilling unit (MODU), that is supported primarily on large pontoon-like structures submerged below the sea surface. The operating decks are elevated 30 m above the pontoons on large steel columns. Once at the desired location, the pontoon structures are slowly flooded until they rest on the seafloor. After the well is completed, the water is pumped out of the pontoon tanks, the vessel refloated and towed to the next location. Submersibles, as they are known informally, operate in relatively shallow water, since they must actually rest on the seafloor.

The water depth range for submersibles is between 3 m and 25 m, with a lesser depth rating during hurricane season. Despite their narrow water depth range, they still serve an important, although limited, segment of the market. Submersibles are attractive in shallow water of less than 4–6 m and/or where the ocean bottom is very soft (less than 2900 N/m^2 shear strength). These soil conditions are common in river delta areas such as around the Mississippi River delta. In these areas, independent-leg Jack-ups may drive their legs well beyond 30 m, and the legs may not be retrievable. Even if a mat-type Jack-up is used, the mat may be submerged, resulting in a loss of mat stability. In these conditions, the submersible becomes attractive. Also, most Jack-up rigs cannot operate in less than 5.5–7.5 m of water, although a very few can move into as little as 4 m of water. However, when they operate in very shallow water, their hull often needs to be placed on the ocean bottom so that their legs can be pulled. Jack-up hulls are not designed for this type of service but they can be used if there are no obstructions

Drilling unit, Ultradeepwater —Ultradeepwater drilling units acquire their name from their ability to drill in 2,300 m, and, in some cases, more than 3,050 m, of water. These units are: extremely expensive, few in number, highly capable, huge in size and technologically advanced. Most have some degree of dual-rig activity (i.e., they have two drilling units on one hull). The Transocean Enterprise Class drill ships (See Figure 9-4), for example, have the capability to run two riser and two blowout preventer (BOP) systems with one system drilling and the other completing a well on a subsea template. With this drill-and-complete mode on a multiwell template, companies have claimed efficiency savings of 40% compared with a single-derrick unit. For exploration wells, it is possible to run casing with one derrick set and drill with the other, thus reducing total rig time to complete the operation. Some have the capability to produce and store crude oil, thus eliminating the need to flare or burn the produced fluid during well testing.

Figure 9-4: Ultradeepwater drill ship Transocean Discover class Discover Deep Seas. There are three of these types of units, which are 254.5 m long with a power rating of 52,000 hp and displacement of 92,800 t. Note the dual crown block for dual activity. Courtesy Transocean.

Ultradeepwater units provided technological breakthroughs in station keeping, re-entry without guidelines, power management, thruster management, reliability, priority assignments, and maintenance that led to the newer units. The newer units are ”D3” rated, in that they have total triple redundancy—if any component of the system should fail, another one comes online immediately; if another system fails, the third system comes online. This approach is an effort to increase the reliability of the total station keeping system and pertains to all system components, including: engines, silicon control rectifier (SCR), electrical switchs, wiring, fuel, thruster, and station keeping monitoring.

Floating liquefied natural gas (FLNG) — A floating liquefied natural gas (FLNG) facility is a floating production storage and offloading unit that conducts liquefied natural gas (LNG) operations for developing offshore natural gas resources. In physical configuration as vessel, a FLNG is similar to a Floating production, storage and offloading (FPSO) platform. Floating above an offshore natural gas field, the FLNG facility produces, liquefies, stores and transfers LNG (and potentially LPG and condensate) at sea before carriers ship it directly to markets.

Floating production system (FPS) — A FPS is typically a large ship equipped with processing facilities and moored to a location for a long period. Because these systems can be moved, they are a more economical solution for more marginal fields, as the vessel can be moved to another development and redeployed once the original field has been depleted.
The FPS is moored in place by various mooring systems—a central mooring system (the turret) allows the vessel to rotate freely to best respond to weather conditions, or weathervane. The system is usually tied to multiple subsea production wells and gathers the oil and/or natural gas through a series of in-field pipelines. Once tapped by subsea wells, the crude oil and natural gas are transmitted through flow lines to risers, which transport the crude oil and natural gas from the seafloor to the vessel’s turret and then to the FPS on the surface of the sea.

Floating, production, storage and offloading (FPSO) — A floating production storage and offloading (FPSO) unit is a floating vessel used by the offshore oil and gas industry for the production and processing of hydrocarbons, and for the storage of oil (See Figure 9-5). The basic design of most FPSOs involves a ship-shaped vessel with a turret to allow it to weathervane with the wind, waves and currents, and with processing equipment, or topsides, aboard the vessel’s deck and hydrocarbon storage below in the double hull. An FPSO vessel is designed to receive hydrocarbons produced by itself or from nearby platforms or subsea template, process them, and store oil until it can be offloaded onto a tanker or, less frequently, transported through a pipeline. FPSOs are preferred in frontier offshore regions as they are easy to install, and do not require a local pipeline infrastructure to export oil. FPSOs can be a conversion of an oil tanker or can be a vessel built specially for the application. A vessel used only to store oil (without processing it) is referred to as a floating storage and offloading (FSO) vessel.
A variation of the FPSO uses a circular hull which shows the same profile to wind, waves, and current regardless of direction. This design shares many of the characteristics of the ship-shaped FPSO such as high storage capacity and deck load, but does not rotate and therefore does not need a rotating turret.

Figure 9-5: FPSO (Turret at the left end of picture).

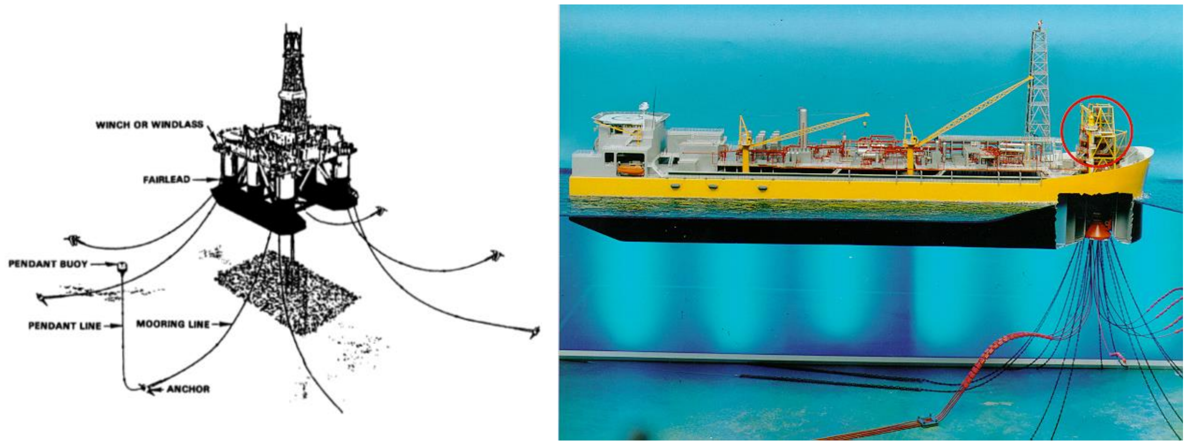
Floating production unit, Semisubmersible (Semi-FPU) — A semisubmersible floating production unit is a semisubmersible which is permanently moored for use as a production platform. The first Floating Production Systems (FPS) were converted semisubmersible MODUs, with permanent mooring systems installed and the drilling systems removed to free up variable load and deck space for production equipment. In many later conversions, particularly for service in Brazil, the drilling equipment was retained to provide either full drilling capability or completion and workover capability. Some new build units were also equipped for full drilling capability. It remained more common, however, for development wells to be drilled by MODUs and tied back to the FPS.

Gravity-based structure (GBS) — A gravity-based structure (GBS) is a support structure held in place by gravity. A common application for a GBS is an offshore oil platform. The GBS is suited for water depths greater than 20 m. These structures are often constructed in fjords since their protected area and sufficient depth are very desirable for construction. A GBS intended for use as an offshore oil platform is constructed of steel reinforced concrete, often with tanks or cells which can be used as in-built oil storage in tanks and to control the buoyancy of the finished GBS. When completed, a GBS is towed to its intended location and sunk. Prior to deployment, a study of the seabed has to be done in order to ensure it can withstand the vertical load exerted on it by that structure. Gravity-based structures are also used for offshore wind power plants.

Mooring, systems — Mooring systems, or more generally “Station-keeping Systems”, are designed for one primary purpose: to protect risers and umbilicals (electrical and control cables to subsea wells and equipment). An offshore drilling or production platform is there to service wells, and this requires a connection. The fundamental function of the platform is to remain safely connected to the well, so if there were no risers or umbilicals there would be no need for a platform. The requirements of the mooring and platform will depend somewhat on the selection of risers. The most stringent requirements relate to top-tensioned or vertical steel risers (“rigid risers”). In this case the vessel offsets must be maintained within 6–10% of the water depth. “Flexible” risers and umbilicals allow offsets of 10–15% of the water depth. Steel catenary risers have requirements somewhere in between these limits.

The two principle types of passive moorings, the “spread” and “single point” moorings are illustrated in Figure 9-6. The spread mooring consists of a number of catenary or taut mooring lines

attached to multiple locations on the platform, which hold the platform on station and in a relatively fixed heading. The single point mooring also consists of a number of catenary or taut mooring lines, but connected to a turret which allows the vessel to rotate. The latter type of mooring is used primarily with ship shaped floating production and storage (FPSO) platforms in order to allow them to weathervane into the heading resulting in a minimum environmental loading.
The forces on a mooring system result from the wave and wind forces on the platform, as well as from the action of currents on the platform. Current becomes a driving design environmental factor in many cases of floating platforms for several reasons. First and most obvious is that large platforms such as semi-submersibles and spars exhibit a large drag area. As a consequence, current loadings can dominate the mooring loads.



Spread Mooring　　Single Point Mooring

Figure 9-6: Mooring systems examples.

The tension leg platform (TLP) has a unique vertical mooring which effectively restricts heave, roll and pitch motions (See Figure 9-7). Surge, sway and yaw restraint is primarily due to the pretension in the vertical mooring lines (“tendons” or “tethers”).

Figure 9-7: Tendon Mooring of a Tension Leg Platform (TLP).

“Catenary” moorings, as the name implies, consist of a number of catenary anchor lines made up of chain, wire or a combination of these. The distinguishing feature of the catenary mooring is that the restoring force of the line is primarily due to the weight of the line.

"Taut" moorings consist of synthetic lines where the restoring force is primarily due to the stretch of the line. These types of mooring are generally made up of synthetic line, usually polyester fibre rope.
Except for the tendon moorings, the mooring does not have a significant effect on the wave frequency responses.

Motion, Vortex induced (VIM) — Flow past bluff bodies at modest velocities results in synchronous vortex shedding—shedding from opposite sides of the structure. This shedding results in an alternating transverse force on the body as well as an alternating force in the direction of flow. For a large diameter body, if the shedding occurs at anywhere near the natural frequency of the platform in surge or sway, the shedding can result in large platform motions known as vortex induced motion (VIM). The use of helical strakes can significantly mitigate this effect.

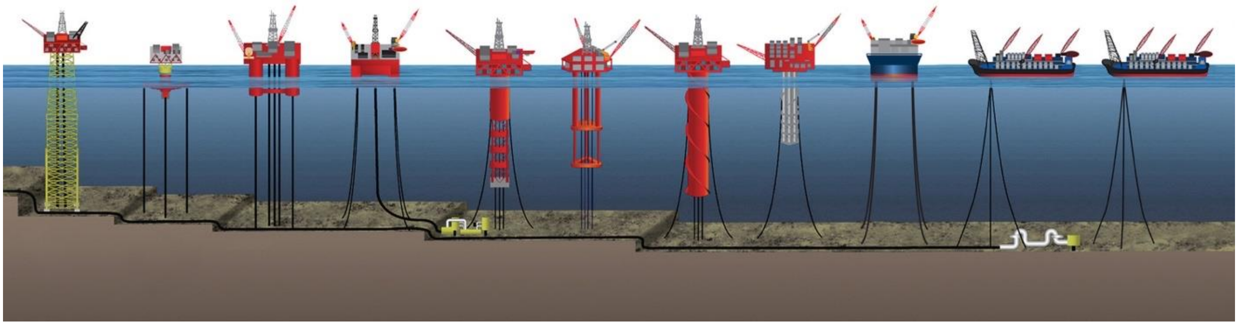
Platform, Fixed — A fixed platform is built on steel legs anchored directly onto the seabed, supporting a deck with space for drilling rigs, production facilities and crew quarters (See Figure 9-8). Such platforms are, by virtue of their immobility, designed for long-term use. Various types of structure are used, steel jacket caisson or floating steel. Steel jackets are vertical sections made of tubular steel members, and are usually piled into the seabed. Fixed platforms are economically feasible for installation in water depths up to about 150 m; for deeper depths a floating production system, or a subsea pipeline to land or to shallower water depths for processing, are usually considered.
Fixed platforms may have as few as 3, or more than 50 well conductors. Generally, the drilling rig is not a permanent part of the fixed structure. However, on some occasions, the unit is left on the platform for future workovers or additional drilling, if removing it is uneconomical. Most fixed platforms are complete, self-contained units that include their own power plant, accommodations, drilling equipment, life-saving equipment, and auxiliary services.

Figure 9-8: Fixed Platform.

Platform, Flexible (Compliant Tower) —A compliant tower (CT) is a fixed rig structure normally used for the offshore production of oil or gas (See Figure 9-9). The rig consists of narrow, flexible (compliant) towers and a piled foundation supporting a conventional deck for drilling and production operations. Compliant towers are designed to sustain significant lateral deflections and forces, and are typically used in water depths ranging from 450 m to 900 m. These structures are considered freestanding but media supported (by water). They demonstrate static stability but have a much greater degree of lateral deformation/flexibility vs land-base structures, up to 2.5% vs 0.5% and are partially supported by buoyancy. It is unknown if these structures could support themselves as built if they were constructed on land. The first compliant tower emerged in the early 1980s with the installation of Exxon's Lena oil platform.

Figure 9-9: Flexible Platform/Compliant Tower.

Platform, Offshore—Offshore platforms are fixed and mobile structures used in the production of offshore energy resources—originally for offshore oil and gas, but more recently also offshore wind energy. All of the platforms remain at a fixed point while in use. The fixed platforms are either attached structurally to the bottom or permanently moored for their lifetime. The mobile platforms are either temporarily moored in place or hold themselves in place by means of a dynamic positioning (DP) system.



1 2 3 4 5 6 7 8 9 10 11

Figure 9-10: Offshore Platforms.

Figure 9-10 illustrates the variety of deepwater offshore platforms that are currently in use: 1) Fixed Platform, rigid or compliant; 2) New construction, tension leg platform (TLP); 3) Conventional, tension leg platform (TLP); 4) Semisubmersible; 5) Truss spar; 6) MiniDOC spar; 7)

Classic spar; 8) Cell spar; 9) Drill ship; 10) Floating production, storage and offloading (FPSO); 11) Floating liquefied natural gas (FLNG).

Platform, Spar — A spar platform consists of a large-diameter, single vertical cylinder supporting a deck (See Figure 9-11). The cylinder is weighted at the bottom by a chamber filled with a material that is denser than water (to lower the centre of gravity of the platform below its centre of buoyancy, providing stability). They are typically used in very deep waters. Additionally, the spar hull is encircled by helical strakes to mitigate the effects of vortex-induced motion. The deep draft design of spars makes them less affected by wind, wave and currents. Spars are permanently anchored to the seabed by way of a spread mooring system composed of either a chain-wire-chain or chain-polyester-chain configuration.

There are three primary types of spars; the classic spar, truss spar, and cell spar. The classic spar consists of the cylindrical hull noted above, with heavy ballast tanks located at the bottom of the cylinder.

Figure 9-11: Spar Platform.

A truss spar has a shorter cylindrical "hard tank" than a classic spar and has a truss structure connected to the bottom of the hard tank. This truss structure consists of four large orthogonal "leg" members with X-braces between each of the legs and heave plates at intermediate depths to provide heave damping. At the bottom of the truss structure, there is a relatively small keel, or soft tank, that houses the heavy ballasting material. Soft tanks are typically rectangular in shape but have also been round to accommodate specific construction concerns. The majority of spars are of this type.

A third type of spar, the cell spar, has a large central cylinder surrounded by smaller cylinders of alternating lengths. At the bottom of the longer cylinders is the soft tank housing the heavy ballasting material, similar to a truss spar.

A fourth type of spar is a miniDOC, which is cross between a semisubmersible and a truss spar—other than this brief description, the miniDOC is not well documented, although the available images appear to indicate that it has numerous small diameter spars in a circular arrangement around a large circular pontoon.

Platform, Tension Leg — A tension-leg platform (TLP) or extended tension leg platform (ETLP') is a vertically moored floating structure normally used for the offshore production of oil or gas, and is particularly suited for water depths greater than 300 m and less than 1500 m (See Figure 9-12). Use of tension-leg platforms has also been proposed for wind turbines.

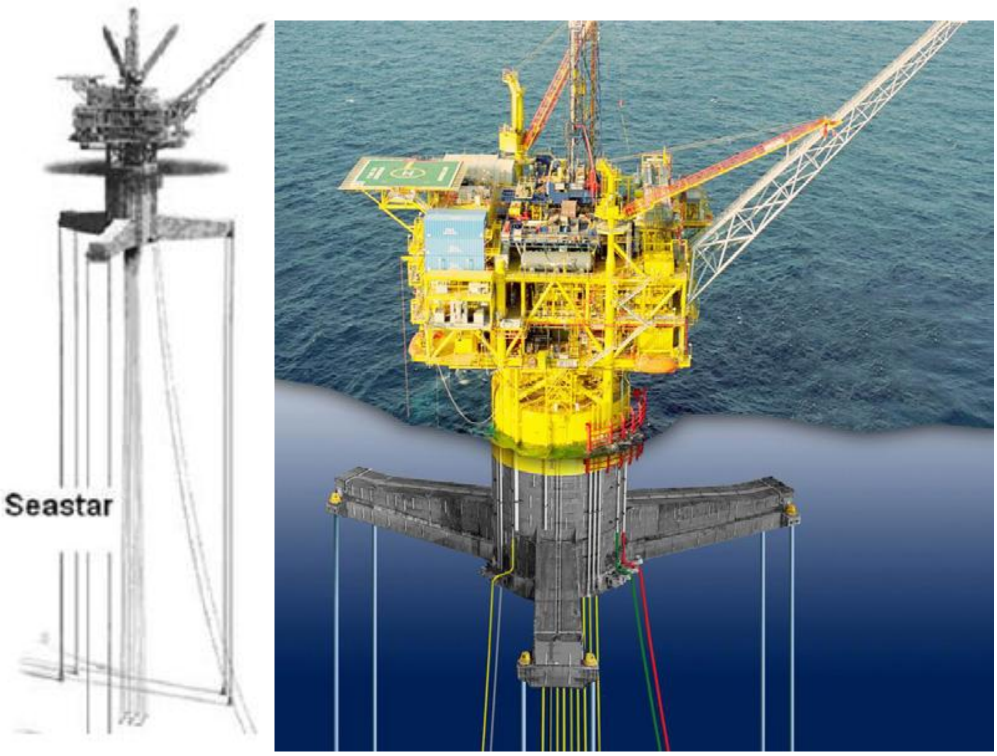


Figure 9-12: Tension Leg Platforms.

The platform is permanently moored by means of tethers or tendons grouped at each of the structure's corners. A group of tethers is called a tension leg. A feature of the design of the tethers is that they have relatively high axial stiffness (low elasticity), such that virtually all vertical motion of the platform is eliminated. This allows the platform to have the production wellheads on deck (connected directly to the subsea wells by rigid risers), instead of on the seafloor. This allows a simpler well completion and gives better control over the production from the oil or gas reservoir, and easier access for downhole intervention operations.

The hull is a buoyant structure, which supports the deck section of the platform and its drilling and production equipment. A typical hull has four air-filled columns supported by pontoons, similar to a semisubmersible drilling vessel. The deck for the surface facilities rests on the hull. The buoyancy of the hull exceeds the weight of the platform, requiring taut moorings or "tension legs" to secure the structure to the seafloor. The columns in the hull range up to 30 m in diameter and up to 110 m in height; the overall hull measurements will depend on the size of the columns and the size of the platform.

The foundation is the link between the seafloor and the TLP. Most foundations are templates laid on the seafloor, then secured by concrete or steel piles driven into the seafloor by use of a hydraulic hammer, but other designs can be used such as a gravity foundation. The foundations are built onshore and towed to the site. As many as 16 concrete piles with dimensions of 30 m in diameter and 120 m long are used (one for each tendon).

Riser — A marine drilling riser is a large-diameter pipe that connects the subsea blowout preventer (BOP) stack to a floating surface rig to take mud returns to the surface. Without the riser, the mud would simply spill out of the top of the stack onto the seafloor. The riser might be loosely considered a temporary extension of the wellbore to the surface. A riser has a large diameter, low pressure main tube with external auxiliary lines that include high pressure choke and kill lines for circulating fluids to the subsea BOP, and usually power and control lines for the BOP. The design and operation of marine drilling risers is complex, and the requirement for high reliability means an extensive amount of engineering analysis is required.

When used in water depths greater than about 20 m, the marine drilling riser has to be tensioned to maintain stability. A marine riser tensioner located on the drilling platform provides a near constant tension force adequate to maintain the stability of the riser in the offshore environment. The level of tension required is related to the weight of the riser equipment, the buoyancy of the riser, the forces from waves and currents, the weight of the internal fluids, and an adequate allowance for equipment failures. To reduce the amount of tension required to maintain stability of the riser, buoyancy modules, known in the industry as 'buoyancy cakes', are added to the riser joints to make them close to neutrally buoyant when submerged.

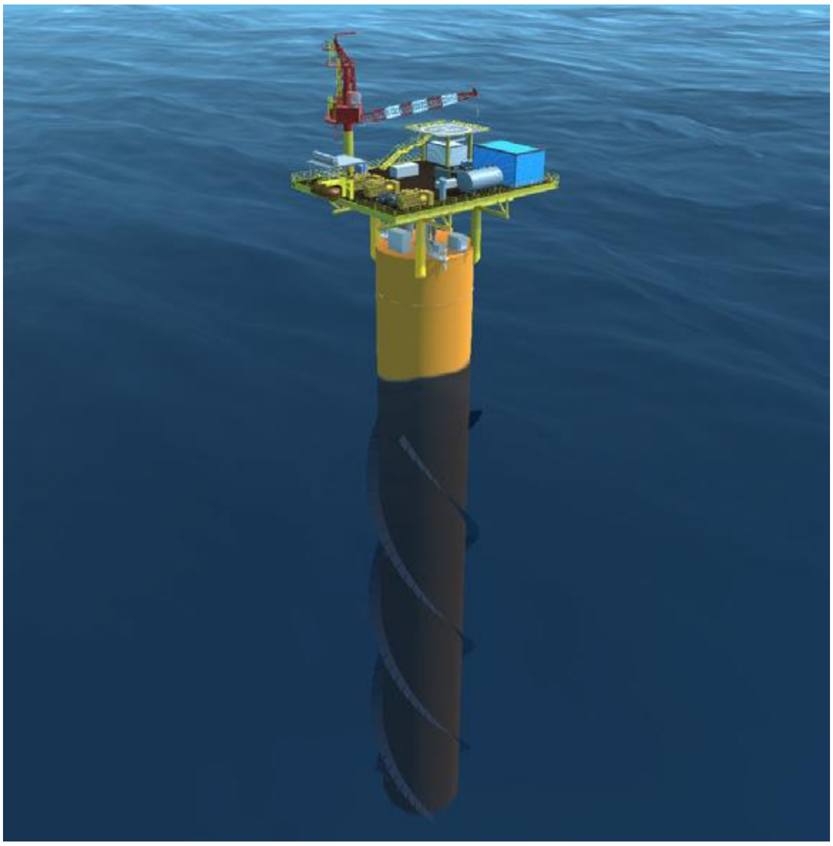


Figure 9-13: Spar Platform with Three Concentric Helical Strakes.

Strake, Helical — Helical strakes are pieces of flat plate oriented normal to the surface of a cylinder and wrapped in a screw-thread pattern with very large pitch (See Figure 9-13). They are known to almost completely reduce VIV on long cylinders by breaking up the span-wise coherence of vortices. Effective helical strakes typically require a height of 0.10–0.12D and a minimum pitch of 5D. These proportions have been used on most spar platforms; however, truss spars in particular have a cylindrical hull with an aspect ratio of less than three. In this case the strakes do not completely eliminate VIM. Furthermore, the combination of the limited span for the strakes, and deleterious effects of hull appurtenances on strake performance lead to a large variation in VIM response from different current directions.

Vessel, Anchor Handler (AHV) — Anchor Handler Vessels (AHV) are mainly built to handle anchors for oil rigs, tow them to location, and to use the anchors to secure the rigs in place (See Figure 9-14). They sometimes also serve as Emergency Response and Rescue Vessels (ERRVs) and as supply transports [Anchor Handling Tug Supply (AHTS) vessels]. Many of these vessels are designed to meet the harsh conditions of the North Sea, and can undertake supply duties there between land bases and drilling sites. They also provide towing assistance during tanker loading and towing of threatening objects.

AHV vessels differ from Platform supply vessels (PSVs) in being fitted with winches for towing and anchor handling, having an open stern to allow the decking of anchors, and having more power to increase the bollard pull. The machinery is specifically designed for anchor handling operations. They also have arrangements for quick anchor release, which is operable from the bridge or other normally manned location in direct communication with the bridge. The reference load used in the design and testing of the towing winch is twice the static bollard pull. Even if AHV vessels are customized for anchor-handling and towing, they can also undertake, for example, ROV (remotely operated underwater vehicle) services, safety/rescue services, and supply duties between mainland and offshore installations.

Anchor handling operations may contribute 10–20% of the total well costs of offshore exploration drilling. In a conventional anchor handling operation, the rig's winches are used to tension the anchors. AHV transports and deploys the anchors, connects the required chains, wires and polyester ropes. AHV can pre-lay the anchors before the rig arrives, and more time can be dedicated to drilling operations.

Figure 9-14: Anchor Handling Vessel.

Vibration, Vortex induced (VIV) — Flow past bluff bodies at modest velocities results in synchronous vortex shedding—shedding from opposite sides of the structure. This shedding results in an alternating transverse force on the body as well as an alternating force in the direction of flow. For a body relatively thin in the direction perpendicular to the flow direction, this shedding can occur at relatively high frequencies resulting in what is known as vortex induced vibration (VIV).
For an offshore platform placed in a current, long vertical cylinders such as risers and the tendons of a tension leg platform (TLP) can suffer from fatigue failures at points where the vibrating component is attached to more rigid structures either at the sea floor or at the platform. This is a particular problem in the Gulf of Mexico (GOM), where there are a number of currents associated with the Gulf Stream. Thus, understanding the metocean environment and the flow conditions on platform components is a critical part of enabling the design of an offshore structure that experiences few structural issues over its lifetime.

10. COMPUTATIONAL FLUID DYNAMICS

This Section is concerned essentially with CFD (Computational Fluid Dynamics), the numerical methods used in hydrodynamics of ships and ocean platforms.

Algebraic equations—Mathematical expressions that involve one or more variables and are formed by equating multiple algebraic expressions. They represent relationships or constraints between the variables and are typically solved to determine the values of the variables that satisfy the given equations.

Artificial dissipation—A technique used in numerical simulations to dissipate spurious oscillations or excessive energy in the solution of partial differential equations, particularly in cases involving discontinuities or shocks.

Asymptotic range—A range of values or conditions in which a system or phenomenon exhibits behaviour that approaches or approximates an asymptotic behaviour, which refers to the characteristics and predictions of a fluid flow as certain parameters approach limiting values or as the flow field extends to infinity.

Comparison error—The discrepancy between the numerical simulation results and experimental data or another reference solution. It includes numerical errors, model errors, errors from boundary conditions, grid and mesh quality, solver convergence, hardware and software, simplifications and assumptions, uncertainty in experimental data, and so on.

Computational Fluid Dynamics—A branch of fluid mechanics that utilizes numerical methods and algorithms to simulate and analyse fluid flow phenomenon.

Conceptual model—A simplified representation of a physical system or a problem under consideration. It serves as the foundation for creating a numerical simulation to analyse and predict fluid flow and related phenomena.

Convergence criterion—A predefined condition used to determine when the numerical simulation has reached a sufficiently accurate solution. Convergence criteria are essential for iterative solvers, which are commonly employed in CFD simulations to solve the discretized governing equations.

Correction factor—A multiplicative factor applied to the results of a simulation to account for discrepancies between the simulated data and experimental or reference data.

Coverage factor—A numerical or statistical measure used to assess the quality and reliability of CFD simulations.

C-type grid—A type of grid commonly used to discretize the computational domain, also known as a non-staggered grid or cell-centred grid. The primary variable values, such as pressure and velocity, are located at the centre of the grid cells.

Data procurement—The process of obtaining and collecting the necessary input data and information required to set up and perform a CFD simulation.

Direct numerical simulation— Direct Numerical Simulation (DNS) is a technique used to simulate fluid flow at the smallest scales, resolving all the details of the turbulent motion. DNS is considered the most accurate approach for simulating turbulent flows but is computationally very expensive.

Discretization scheme—A numerical approach used to approximate and solve the governing equations of fluid flow within a computational domain. The fundamental governing equations are typically the Navier-Stokes equations, which describe the conservation of mass, momentum, and energy. Discretization is the process of converting these continuous partial differential equations into a set of discrete algebraic equations that can be solved on a computer.

Divergence—The divergence of a vector field in the continuity equation, which ensures the conservation of mass within the domain. It can also refer to “numerical divergence”, which indicates a violation of the continuity equation and is a condition that needs to be resolved to maintain the accuracy and reliability of the CFD simulation.

Explicit scheme—A computational approach where the solution of a mathematical problem is obtained by expressing the variables at the next time step solely in terms of their current values and known parameters in numerical methods.

Factor of safety approach—A concept commonly used in engineering and design to ensure the reliability and safety of a structure or a system. It can be applied in conjunction with CFD analysis to evaluate the structural integrity or safety of components subjected to fluid forces.

Finite-difference method—A numerical technique used to approximate solutions to differential equations by discretizing the domain into a grid and approximating derivatives using finite difference approximations.

Functionality—The capabilities and features of CFD software and tools that enable engineers and researchers to simulate and analyse fluid flow and related phenomena. CFD software provides a range of functions and capabilities to perform simulations, and these functionalities can vary from one software package to another.

Generalized Richardson extrapolation—A numerical technique to improve the accuracy of simulation results, especially for problems with known discretization error. Richardson extrapolation is a method that combines solutions from simulations with different grid resolutions to estimate a more accurate solution, effectively reducing the discretization error.

Global convergence ratio—A measure used to assess the convergence behaviour of an iterative numerical method. It means how quickly the method converges to the solution as the number of iterations increases. It is defined by the ratio between the error at the current iteration and the error at the next iteration.

Grid convergence—The property of a numerical solution obtained using the finite-difference, finite-element, or finite-volume method, where the solution approaches the exact or reference solution as the grid is refined.

Grid convergence index—A quantitative measure used in grid convergence studies to assess the accuracy and convergence behaviour of numerical solutions obtained on different grid sizes.

Grid dependence—The phenomenon where the solution obtained from a numerical simulation depends significantly on the size or resolution of the computational grid.

Grid size—The spacing or resolution of the computational grid used to discretize the problem domain.

Grid-refinement ratio—The ratio between the sizes of two different grids used in a simulation. The grid-refinement ratio is typically used in the context of grid convergence studies to assess the convergence of numerical solutions to a well-resolved and accurate result.

Higher-order upwind finite differences—A class of numerical discretization schemes to approximate the spatial derivatives of the governing equations, such as the convection term in the Navier-Stokes equations. These schemes are designed to provide higher accuracy and improved resolution of flow features, especially in cases with strong gradients and discontinuities.

H-type grid—A grid structure commonly used, also known as a hybrid grid. It combines elements of structured and unstructured grids to discretize the computational domain.

Ill conditioned—A mathematical problem or system that exhibits sensitivity or instability when small changes are made to the input or data.

Implicit scheme—A computational approach where the solution of a mathematical problem is obtained by solving an equation or system of equations that involve future or unknown values of the variables in numerical methods.

Initial condition—The starting value or set of values assigned to variables or functions at the beginning of a process or calculation in various mathematical and computational contexts.
Iteration number—The count to each iteration in an iterative process or algorithm.
Iterative convergence—The behaviour of an iterative process as it approaches a desired solution.
Iterative errors—The discrepancies or differences between the approximations obtained at each iteration of an iterative process and the true or desired solution.
k-ε turbulence model—A two-equation model that provides a simple and computationally efficient way to simulate turbulence in a variety of flows. The k-ε turbulence model is based on the idea that turbulence is driven by two transport equations, one for turbulent kinetic energy (k) and another for the rate of dissipation of turbulent kinetic energy (ε). The model assumes that these two quantities are the primary indicators of turbulence characteristics.
k-ω turbulence model—A two-equation model that describes turbulence based on two transport equations. The k-ω model is based on the concept that the turbulence characteristics are primarily governed by two quantities: turbulent kinetic energy (k) and specific rate of turbulence dissipation (ω). These two variables provide information about turbulence intensity and its decay rate.
Large eddy simulation— A computational fluid dynamics (CFD) approach that aims to simulate the most energetic large-scale turbulent structures explicitly while modeling the effects of the smaller, unresolved turbulent scales.
Maintainability—The ability to sustain and manage CFD simulations, software, and associated infrastructure over time to ensure the reliability, accuracy, and longevity of the CFD practice. Maintaining a CFD workflow is essential for achieving consistent and reliable results while managing resources efficiently.
Modeling error—Many CFD simulations involve turbulence modeling to simulate the effects of turbulent flow. Errors can arise from the choice of turbulence model and its associated constants or coefficients.
Monotonic convergence—The property of a numerical method or algorithm where the sequence of iterates generated by the method consistently approaches the true solution, without oscillations or divergence.
Non-orthogonal grids—Computational grids that do not align with a Cartesian coordinate system.
Numerical benchmark—Well-defined test cases or benchmark problems to assess the accuracy and performance of CFD solvers, models, and numerical methods.
Numerical error—CFD simulations involve the discretization of the governing equations using numerical methods. Errors can occur due to the choice of grid resolution and the numerical scheme used.
Order-of-accuracy—The level of precision or the rate at which the error in a numerical solution decreases as the grid or mesh size is refined. It is a measure of how closely a numerical method approximates the true solution of the governing equations.
Orders-of-magnitude—A way of expressing the relative size, scale, or difference between quantities. It is a logarithmic measure, typically base 10, that helps understand the scale of numbers, making it easier to compare and analyse them.
Oscillatory convergence—A situation where the iterative solution process exhibits repetitive, alternating behaviour during convergence, leading to apparent oscillations in the residuals or other convergence monitoring parameters.
O-type grid—A specific type of structured grid commonly used for simulating fluid flow in two-dimensional or axially symmetric problems. O-type grids are characterized by their concentric circular or annular grid lines, which resemble the letter "O."

Parameter convergence—The process of determining and ensuring that the simulation results are reliable and accurate with respect to the user-defined input parameters. These parameters can include grid resolution, time step size, turbulence model settings, boundary conditions, and other simulation-specific settings. Parameter convergence is essential for obtaining physically meaningful results in CFD simulations.

Parameter refinement ratio—The ratio that quantifies the effect of refining a specific parameter, such as grid resolution, time step size, or turbulence model settings, on the accuracy and reliability of CFD simulation results. The parameter refinement ratio is used to assess how changes in these parameters influence the simulation's performance and predictive capabilities.

Point variable—A value associated with a specific point in space or time within a domain.

Portability—The ability to run CFD simulations and related software on different computing platforms, such as different operating systems and hardware architectures, without major modifications or issues.

Posteriori—Posteriori error estimation or posteriori analysis. Posteriori error estimation can involve various techniques, such as comparing simulated results with experimental measurements, analysing convergence behaviour, and assessing the sensitivity of the solution to changes in input parameters. Posteriori analysis is an important step in the validation and verification process for computational models, ensuring that the simulated results align with observations and providing insights into the strengths and limitations of the numerical approach.

Post-processing—The phase of analysing and visualizing the simulation results after running a CFD simulation. It plays a crucial role in understanding the behaviour of fluid flow, extracting meaningful information, and communicating the findings to engineers, scientists, and decision-makers.

Pre-processor—A crucial component of the simulation workflow. It is responsible for preparing the simulation by setting up the necessary input data and conditions before the CFD simulation is run.

Pressure-Implicit with Splitting of Operators (PISO) —A numerical algorithm that improves the accuracy and stability of CFD simulations, particularly when dealing with transient and incompressible flows. The PISO method starts with an initial guess for the velocity field. After obtaining the tentative velocity field, the pressure field is corrected to ensure that it satisfies the continuity equation. With the corrected pressure field, the final velocity field is calculated to be used in the next time step.

Quality assurance procedures—The procedures help verify that the simulations are conducted according to best practices, meet industry standards, and produce valid results.

Reliability—The confidence and trustworthiness of CFD simulations and their results.

Reynolds Averaged Navie Stokes (RANS) —A set of partial differential equations used to model and analyse the behaviour of turbulent fluid flow. RANS equations aim to simplify a wide range of turbulent scales by averaging out the turbulent fluctuations over time, resulting in a set of equations that provide mean flow quantities. Additional modeling is required for the Reynolds stresses, which capture the turbulent fluctuations.

Reynolds stress—Fluctuating stress caused by the random and chaotic motion of fluid particles in turbulent flows.

Sensitivity—The impacts of changes in various input parameters, boundary conditions, or model settings on the results of a CFD simulation

Simulation uncertainty—The inherent variability and potential error associated with numerical simulations of fluid flow.

Single block— The entire computational domain is discretized using a single, contiguous mesh block. This contrasts with a multi-block approach, where the domain is divided into multiple non-overlapping blocks, and each block can have its own mesh structure.

Spatial discretization—The process of approximating the continuous physical domain into a discrete grid or mesh.

Spatial order of accuracy—The level of precision in approximating spatial derivatives of the governing equations for fluid flow.

Structured grid—A grid system that is characterized by a regular and systematic arrangement of grid cells or elements.

Time integration—The numerical methods used to advance the solution of the governing equations for fluid flow in time.

Time step—The discrete intervals at which the simulation progresses in time.

Truncated term—A situation where a term or component in the governing equations has been omitted or simplified during the modeling process. This truncation can occur for various reasons, such as simplifying assumptions, computational constraints, or the need to reduce the complexity of the simulation.

Truncation error—The discrepancy between the exact mathematical solution of the governing equations for fluid flow and the numerical approximation of that solution. It is a type of error that arises because of the discretization of space and time when solving partial differential equations numerically.

Turbulence closure models— Turbulence closure models account for the effects of turbulence in the flow field by providing closure to the governing equations, specifically the Reynolds-averaged Navier-Stokes (RANS) equations. These models help represent the turbulence-related quantities that arise due to the averaging process in RANS equations.

Turbulence model— Turbulence is a complex and chaotic motion of fluid particles, and resolving all the turbulent scales directly is often computationally infeasible. Turbulence models provide a practical way to account for the effects of turbulence and predict its impact on fluid flow.

Under-relaxation—A numerical technique used to stabilize and control the convergence of iterative solvers for the solution of fluid flow problems. It involves adjusting the rate at which the solution variables at each computational grid point or cell are updated during the iterative process.

Unstructured grid—Unstructured grids differ from structured grids in that they are not based on a regular, uniform arrangement of grid cells but rather consist of an irregular arrangement of cells, which can vary in size and shape.

Usability—The ease with which CFD software and tools can be used by engineers, scientists, and researchers to set up, run, and analyse CFD simulations.

Validation—A crucial process that involves comparing the results of a CFD simulation with experimental or analytical data to assess the accuracy and reliability of the computational model and methodology.

Validation uncertainty—The quantification of the uncertainty associated with the comparison of CFD simulation results with experimental or analytical data during the validation process.

Verification—A process aimed at ensuring the correctness and accuracy of the numerical methods, algorithms, and software used for simulating fluid flow.

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9. IMO_SLF51/4/1 ANNEX III

Draft terminology for the new generation intact stability criteria

11.1.1 General

Stability	A ship is stable if, upon being inclined by external forces, it returns to the initial position when action of these forces ceases to exist
Intact stability	Stability of a ship without any damage to its watertight buoyant space, hull structure or to any onboard system that could lead to loss of buoyancy due to water ingress
Standard	is a boundary separating acceptable and unacceptable likelihood of failure
Operational guidance	Recommendation, information or advice to an operator aimed at decreasing the likelihood of stability failures and /or their consequences
Loading condition	Characterization of the components of a ship mass and its distribution. A Typical description of loading conditions includes mass displacement, co-ordinates of the centre of gravity and radii of inertia for three central axes and tanks with free surfaces and corresponding inertia effects.
Operational parameters	Parameters that can be controlled by a ship operator; for a self-propelled ship which may include, but not limited to, commanded course angle, commanded propeller revolution, trim, heel, rudder angle, operational GM
Environmental conditions	A set of parameters and functions describing parameters of wind, waves and currents and that are sufficient for an adequate modelling of possible stability failures, including but not limited to: Waves: number~~,~~ significant wave height, characteristic period (modal/peak, mean, zero-crossing period), directional spectrum; Wind: direction, mean speed, spectrum of wind speed fluctuations, spectrum of transversal fluctuations, profile, coherence. Current: direction, mean speed, width and speed profile
Safety Level	is a number related to a likelihood of failure, including, but not limited to a probability of failure during finite period of time. The term “Safety level” is further understood as a level of safety from stability failure. Safety level is a standard for probabilistic performance based criterion.

Rule/Regulation	is the specification of a relationship between a standard and the value produced by a criterion

11.1.2 Criteria

Criterion	is a procedure, an algorithm or a formula used for judgment on likelihood of failure
Vulnerability criterion	Vulnerability criterion are intended to distinguish between conventional and unconventional ships
Unconventional ships	Ships that are vulnerable to unconventional stability failures
Parametric criterion	A criterion based on a measure of a quantity which is related to a phenomenon, but does not contain a physical model of the phenomenon. [probabilistic (e.g. the new damage stability criterion in *Res. MSC.216(82)*) or deterministic (e.g. the *GZ* curve criterion in §2.2 of the *Revised IS Code*)]
Performance-based criterion	A criterion based on a physical model of a stability failure. [probabilistic (e.g. *SLF 49/5/5* and *SLF 49/INF.7*) or deterministic (e.g. *SLF 49/5/6*)]
Probabilistic criterion	A criterion considering stability failure as a random event. [performance-based (e.g. *SLF 49/5/5* and *SLF 49/INF.7*) or parametric (e.g. the new damage stability criterion in *Res. MSC.216(82)*)]
Deterministic criterion	A criterion considering stability failure in a deterministic manner. [performance-based (e.g. *SLF 49/5/6*) or parametric (e.g. the GZ curve criterion, §2.2 of the *Revised IS Code*)]
Probabilistic performance-based criterion	is a criterion based on a physical model of a stability failure considering this phenomenon as a random event.
Deterministic performance-based criterion	is a criterion based on a physical model of a stability failure considering this phenomenon in a deterministic manner.
Probabilistic parametric criterion	is a criterion based on a measure of a quantity related to a phenomenon, but does not contain a physical model of the phenomenon, and includes one or more stochastic values.
Deterministic parametric criterion	is a criterion based on a measure of a quantity related to a phenomenon, but does not contain a physical model of the phenomenon, while all the input values are deterministic.

Direct safety assessment	A means of assessing risk from theoretical calculation or model experiments rather than by comparison with empirical or semi-empirical criteria
Conservative envelope	Is a boundary based on operational parameters intended to separate safe from unsafe ships but with a large inbuilt safety margin.
Rate of failures	Expected number of failures per unit time

11.1.3 Intact Stability Failure Events

Heel	is the degree to which a ship leans transversely as a result of variable and dynamic external forces
Roll	is the continuous response of the ship in a transverse direction to variable and dynamic external forces.
List	is a transverse rotation of the ship about a vertical axis through the centreline arising from static forces in equilibrium and is usually measured by the difference in draught amidships between the port and starboard sides.
Intact stability failure	a state of inability of a ship to remain within design limits of roll (heel, list) angle and combination of lateral and vertical accelerations
Total stability failure *or capsizing*	Total loss of a ship's operability with likely loss of lives. Capsizing could be formally defined as a transition from a nearly stable upright equilibrium that is considered to be safe, or from periodic motions near such equilibrium, to another stable equilibrium that is intrinsically unsafe (or could be considered fatal from a practical point of view).
Partial stability failure	Occurrence of very large roll angles and/or excessive roll accelerations, which will not result in loss of the ship, but which would impair normal operation of the ship and could be dangerous to crew, passengers, cargo or ship equipment
Unconventional stability failure	Is a stability failure not explicitly (and/or sufficiently) covered by Part A – Chapter 2 “General Criteria“ and Chapter 3 ”Special Criteria for Certain Types of Ships”, and in particular a type of stability failure addressed by Part A - §1.2 “Dynamic stability phenomena in waves
Vertical acceleration	Acceleration component perpendicular to the deck, positive downward
Lateral acceleration	Acceleration component parallel to the deck, positive starboard

11.1.4 Measurement

Probability of stability failure	is a probability or an estimate of probability that at least one stability failure will occur during an exposure time
Exposure time	It is the time interval to be used for stability judgement using short-term probabilistic criteria
Long-term formulation	A way to estimate the probability of a stability failure in the time scale of days, months or years, where changing sea state, course and speed, as well as variation of loading condition, are taken into account
Short term formulation	A way to estimate the probability of a stability failure in a time scale within the range of several hours, using the assumption of stationary (in statistical sense) environmental conditions.
Assumed situation	A combination of loading conditions, environmental conditions and operational parameters, as well as time of exposure.

11.1.5 Modes of Stability Failures

Regular waves	A strictly periodic wave characterised by one fundamental harmonic component and possible additional, usually small, harmonic components due to the nonlinearities of the free surface
Irregular waves	A sea surface process that cannot be characterised as a regular wave. It is usually, but not only, defined by means of a spectrum
Parametric rolling	is an effect of amplification of roll motion of a ship due to periodic changes of restoring moment causing parametric resonance. Periodic changes of restoring moment may be caused by wave pass effect and or coupling with other degrees of freedom (e.g. MSC.1/Circ.1228 for phenomena explanation).
Synchronous rolling	roll motion induced by an external excitation force having its frequency equal to the natural roll frequency
Broaching-to	a phenomenon where a ship cannot keep constant course despite maximum steering efforts and experiences a significant yaw motion in an uncontrolled manner
Surf-riding	a phenomenon where mean speed of a floating body is shifted from the original one to wave celerity because of wave actions (e.g. MSC.1/Circ.1228 for phenomena explanation).
Dead-ship condition	Condition under which the main propulsion plant, boilers and auxiliaries are not in operation due to the absence of power. (SOLAS II-1/3,8)

Pure loss of stability	Condition under which static balance in heel is lost due to reduction of righting lever curve or increase of heeling moment

11.1.6 Methodology

Physical model	In this framework this term is used to indicate a theoretical model based on a physical description of the involved phenomena.
Numerical simulation	A method of replicating to an approximate degree the results of physical model tests using numerical methods on a computer model of the hull with due allowances for environmental conditions
Analytical solution	Solution expressed in a form of well-known operations, including elementary and special functions as well as infinite series.
The time scale split method	A method in which the problem of irregular roll and capsizing (or reaching large roll angle) is divided in two (or more) sub-problems
Statistical extrapolation	A method that uses an assumed theoretical distribution to fit an available set of data and to eventually extrapolate the results outside the original data range. It is usually used to obtain information on the tails of the distribution of roll angles and/or rolling amplitude

12. OVERALL INDEX OF TITLES