The Specialist Committee on Waves

Final Report and Recommendations to the 23rd ITTC

1. GENERAL

1.1. Membership and meetings

The committee appointed by the 22nd ITTC consisted of the following members:

- Dr. Carl Trygve Stansberg, Norway (chairman),
- Dr. Giorgio Contento, Italy
- Dr. Seok Won Hong, Korea
- Dr. Mehernosh Irani, USA (until 1 January 2002)
- Dr. Shigesuke Ishida, Japan
- Dr. Richard Mercier, USA (from 1 January 2002, replacing Mehernosh Irani)
- Prof. Yanying Wang, China
- Prof. Julian Wolfram, UK

Corresponding members:

- Prof. John Chaplin, UK
- Prof. David Kriebel, USA.

Four committee meetings held at:

- ISOPE Conference, Seattle, USA, June 2000.
- University of Trieste, Italy, Dept. of Naval Architecture, Ocean and Environmental Engineering, January 2001.
- MARINTEK, Trondheim, Norway, June 2001.
- OTRC, Texas, USA, March 2002.

1.2. Recommendations of the 22nd ITTC

The 22nd ITTC recommended that the Waves Committee should carry out the following work:

- Review and update recommended wave spectra including 2-parameter spectra, short-crested seas, fetch limited, b-modal spectra, and finite depth spectra.
- Examine wave generating procedures with respect to wave quality in both deep and shallow water, such as spectral shape, multidirectional waves, wave groups, extremes, and wave-current interactions, and develop guidelines for this quality during model tests.
- Procedures must be in the format defined in the Manual of ITTC Recommended Procedures and they should be included in the Committee Report as separate appendices. Symbols and terminology should agree with those used in the 1999 version of the ITTC SaT list, new symbols should be proposed.
- The compatibility of ITTC and coastal engineering practices for modeling shallow and finite water depth should be investigated.
- The Committee must consult with IAHR.

The following chapters detail the tasks undertaken by the Committee:

Chapter 2	Introduction
Chapter 3	Purposes of Wave Modeling and Types of Data

2. INTRODUCTION

The 23rd ITTC Specialist Committee on Waves was established at the 22nd ITTC in Shanghai, China, September 1999, and is working within the frame of a 3-year period until the 23rd ITTC in Venice, Italy, September 2002. As a part of the tasks of the previous 22nd ITTC Specialist Committee on Environmental Modelling, an overview and brief discussion of various topics within wave modelling was made, which forms the basis of the present work. Spectral formulations were addressed by the 22nd ITTC Loads and Responses Committee. Wave modeling has also been addressed previously by the 17th ITTC.

The idea of the present Committee Report is not to repeat previous works, but rather to review and discuss particular topics considered critical for the quality of the generated waves. This certainly depends upon the actual type of application, and the relevance of wave parameters and characteristics may vary from case to case. Furthermore, there is a diversity of applications and laboratory lay-outs, and it is therefore a complex task to define procedures and guidelines for wave modeling in general.

During the work with this report, it therefore became clear that at the present stage, one is unable to conclude with particular recommended procedures to the ITTC, but some generally accepted methods and standards have been identified. These, which should form the basis for future ITTC recommended procedures, are described and discussed in the following, after initial considerations on wave modeling purposes and types of input data (Chapter 3).

The report addresses the quality of reproduced waves only, and not the quality of full-scale input data, which is considered to be outside the scope of the work. Main topics include spectral shape and bi-modality, directionality, non-linearities and extremes, transient waves, waves on current and on finite water, and numerical modeling and its interaction with model testing. These are considered to be critical topics, and are also of current interest within research. Well-defined references and standards are essential for the quality, and are therefore addressed in particular. As a part of that, a separate Appendix with frequently used spectral formulations is enclosed with the report. Commonly known generation techniques, previously described by the ITTC are, however, not repeated in detail.

3. PURPOSES OF WAVE MODELLING AND TYPES OF DATA

3.1. Why are we doing this?

Wave modelling is required for experiments on a wide range of different types of physical models in order to estimate loads and responses for design, operation and regulation. Wave modelling is also required as an input to any numerical or theoretical analysis; and physical model tests in waves are used for the validation of numerical tools. Specific model experiments are also undertaken as part of accident analysis.

3.2. Types of vessels and structures

There is a growing diversity of model types. Conventional monohull ships range from small fishing vessels and yachts to large VLCCs. There is also a wide range of multi-hull and surface effect vessels that are tested at high speed in waves. Models of offshore structures may be fixed, articulated or floating, and an offshore system may comprise both fixed and floating elements that must be tested together; e.g. a semi-submersible attached by a bridge link to a fixed jacket structure, or a shuttle tanker attached to the stern of a FPSO. Moorings, tension legs or dynamic positioning arrangements must also be modelled as part of the offshore system.

Models may either be nominally rigid or designed to produce appropriate hydroelastic responses. Where high Reynolds numbers are needed only single elements may be modeled; for example the tubular of a jacket structure (Sumer & Fredsoe, 1997) or a section of a flexible riser. Experiments in waves are also undertaken with models of large offshore breakwaters, floating island airports and wave energy devices.

3.3. Responses

Responses can be broadly classified into linear and non-linear, with non-linear responses mostly (but not always) associated with extreme conditions. Linear and quasi-linear quantities, e.g. motions in six degrees of freedom and relative wave elevations, are often investigated by a series of tests in regular waves and the results expressed as transfer functions (response amplitude operators). Transfer functions are also obtained from irregular wave experiments where the waves are generated as a pseudo-random time series from a given wave energy spectrum. Assuming linearity, a quicker experiment in transient waves is possible (Clauss & Steinhagen, 1999). Experiments may be undertaken in either long-crested or short-crested seas and in experiments with a moving vessel, the wave conditions actually encountered by the model must be considered. In this case the spatial and temporal variations of the wave conditions over the operational area of the tank are important. In high-speed craft, particularly multi-hulls, wave-induced accelerations and passenger comfort tions and passenger comfort can be a limiting factor. The most severe accelerations may occur in oblique seas, for which tests in either short or long crested seas in a wide tank will be required (linear responses in real sea conditions are estimated by using the transfer functions in combination with wave spectra and wave statistics).

Some non-linear quantities like added resistance are also treated by using transfer functions – as long as they can sensibly be evaluated using the same procedure as for linear quantities. By changing the wave height in regular waves or spectral energy in irregular waves the non-linearities may be studied in the laboratory. It is important that when there are non-linearities the waves used in the model experiments are of similar scale, size and frequency to those of interest, otherwise extrapolation may lead to significant errors.

Floating offshore structures are held on station by moorings, tension legs or dynamic positioning, and these systems are modeled in experiments to give the appropriate stiffness characteristics and frequency response. When more than one structure is modeled, the response may be complex because of interactions between them; there will be a wide range of natural frequencies for the various responses. Natural periods can range from the very short for hydroelastic responses to the very long for a floating structure with deep moorings. In the first case the transient responses excited by the slamming, slapping or pounding of a single large steep wave is significant and in the latter case the response may be at the wave group frequency. It is important here also that the random sea state produced in the tank reflects both the individual wave characteristics and wave group characteristics of the real sea.

Very large floating structures such as floating breakwaters and airports require consideration of the spatial coherence of the wave field over the area they occupy in the tank or basin. They will also generate significant wave reflections that must be considered. In shallower water the modification of the wave profile and wave particle kinematic field will affect loads and responses. Bathymetric variations will also be important.

3.4. Extremes

Extreme responses are often highly non-linear and are usually associated with extremely high and/or steep waves. For example, when examining the air-gap between the crest of the extreme 'design' wave and the underside of the deck of a semi-submersible, the non-linearity of both the wave and the motion response of the vessel are important.

Rough weather phenomena such as slamming, green water on deck and capsizing are examined in regular waves. However measurements in irregular waves are indispensable because transient effects are important when the vessel is close to resonance. For the capsizing of damaged RoRo vessels the history of water accumulation on the vehicle deck is crucial. Wave front steepness is an issue here. The statistics of wave groups, crest height and steepness should be representative of the real sea if these responses are to be predicted accurately.

Stability problems in following or quartering seas, broaching, pure loss of stability, parametric oscillation and bow diving of fast ships, are sometimes investigated in regular waves because the conditions that give rise to these events, which have low encounter frequencies can be approximated in this way. On the other hand, studies on capsizing using steep breaking waves are often carried out in concentric transient deterministic waves as one realization of freak waves. The probability of capsize is directly related to the probability of encountering dangerous wave situations.

For many offshore structures and systems, extreme loads and responses occur as a combination of waves, wind and current. For fixed structures the extremes are usually the result of a collinear combination of wave, wind and current. Tests on floating structures, for which this is generally not the case, must be done in a wide tank. The effect of current on the waves is to modify the surface profile as well as the water particle kinematics, and this will depend on their relative directions.

For design purposes it is usually the 'expected' extreme response (in the statistical sense) that must be estimated. However, there will inevitably be variations in the extremes from one random time series to the next. Thus measured extreme responses will vary from one experiment to the next even when the random wave time series are generated from the same design spectrum. Thus it is important to ensure that the statistics of the individual wave parameters and wave group parameters for the random wave time series are close to the 'expected' values.

In some experiments, for example on ringing or wave impact, it may be necessary to reproduce the same time series reliably.

3.5. Sources of data

In order to establish parameters for modeling in waves, the selection and collection of wave data are important both for short-term prediction and long-term analysis. For engineering practice, wave data can be divided into two types, i.e. short-term observation data and the long-term analytical data.

Short-term wave data may be obtained from wave buoys, offshore platforms, station observations, ship observations, and satellite databases. Hindcast techniques have now reached a reasonable state of maturity (Cardone & Resioo, 1998). Most hindcasts use wind fields as the primary input source for an energy balance-based wave model but have been adapted to include wave observations where these are available. Detailed hindcasts using a fine spatial grid (a few kilometres square) have been made for many areas of the world. The output from hindcasts can provide directional spectra characteristics as well as Hs and Tz, but does not provide information on individual waves or wave groups. It is necessary to distinguish between wind-driven waves and swell since these often come from different directions and usually have different peak frequencies resulting in bimodal spectra. Swell is important in offshore field areas such as West of Shetland and particularly off West Africa (Cardone et al., 1995). In practice, the usefulness of any wave data relies on detailed documentation, and the following points need to be considered.

(1) Generally it is difficult for a designer to obtain the original wave data as a time series. What is generally available are overall descriptions for given sea-states. From these spectral descriptions average, significant and expected (1/n maximum) extreme waveheights can be estimated using random linear theory. Wave period characteristics can also be estimated. There are theoretical models, based on random linear theory, for predicting the joint probability of individual wave heights and periods and more recently empirical models have been developed using wave data for estimating the joint probability of wave height and steepness (Wolfram et al., 2001).
(2) Each sample record in the wave data denotes a special sea-state in which the corresponding environment data is also useful for designers such as speed, direction, and duration of wind and location (in longitude and latitude) for the effective area of the wave data.
(3) The development of satellite data, as an alternative to ship observations, has been slower than might be expected. One reason for this is that only the altimeter (which can measure significant wave height) is operating at all times, while the SAR (Synthetic Aperture Radar – which can measure wave direction and length for long waves) is in intermittent operation because of its power consumption. Moreover Cooper & Forristall (1997) state that some satellite databases are not sufficiently documented, and the reason for the delay in satellite data acceptance may thus be a lack of training in the methods necessary to tackle this new source of data. However there are now efforts to coordinate the analysis of satellite and other remotely sensed data (HF radar) in the EU funded MAXWAVE project programme, and direct estimates of individual extreme wave heights are now being made from these data (Rosenthal, 2002). Satellite databases are becoming an important wave source for engineering application and GEOSTAT based world wind and wave data atlases are now being published (Young & Holland, 1996) .

Long-term wave statistics can be estimated from the analysis of outputs from series of short-term wave data analyses. In design practice, the survival condition for ocean structures is limited under an extreme sea-state, generally the so-called 100-year wave H_{100}, defined as the maximum wave with a return period equal to 100 years. For offshore structures it is usual to estimate the 3-hour sea-state, as characterised by Hs, Tz or Tp, with a return period of 50 or 100 years and then to predict the expected maximum individual wave height and associated period in this sea-state.

For ships, long term predictions are often based on the number of waves likely to be encountered over the whole life of the ship (assumed to be 20 years), typically 10^8. The 100- or 20-year maximum wave has a very small occurrence probability, and its prediction should be based on a large sample of short-term distributions in order to assess the associated confidence level. In connection with this, there are two topics that should be discussed:

(1) It is well known that a large volume of wave data is required to ensure a reliable prediction of design waves. For ships, world-wide wave statistics along sea routes are necessary. Generally, wave observations are of rather limited duration and the derivation of design conditions therefore calls for an analytical method such as the maximum entropy approach.
(2) The Weibull probability density function has been widely applied to fit the cumulative probability of short-term wave data.

The derived design wave parameters should be accompanied by their standard deviations and a measure of the corresponding confidence levels. For world-wide statistics GWS (Global Wave Statistics, Hogben et al., 1985) is often used. These provide wave data estimated from observed wind speeds.

In fact the 100- or 20-year wave height is just one aspect necessary for design and rule-making. Evaluation of loads and responses over the lifetime of the vessel is necessary for safe, economical operation and comfort of crews and passengers. For that purpose the scatter diagrams of wave height and period are available in publications such as GWS and those from DNV. For more detailed information, wave spectra and directional distributions are required (see Chapter 5).

It is recommended that standard procedures and expressions should be formulated by ITTC for processing measurements and predictions. Wave data and analytical results from different regions and provided by different institutions could then be compiled by similar procedures. Measured wave data and derived statistical functions can be used not only in engineering design but also in the simulation in the laboratory for analysis of motions and loads in waves for ships and floating structures.

4. WAVE MODELLING AND QUALITY IN MODEL TESTING

The generation of water waves in the laboratory is subject to a range of different reference parameters or standards, reflecting the diversity of applications referred to in Chapter 3. Previously, a broad survey with evaluation and recommendations of techniques was given in the 22nd ITTC Report on Environmental Modelling. In the following, specific wave properties and model testing conditions, considered critical for the quality of wave modeling, are highlighted. A complementary overview, roughly illustrating the relevance to applications, is given in Tables 4.1, 4.2 and 4.3 (the tables are tentative, and are certainly a topic of discussion). Accurate definitions of parameters and conditions specified and used in tests is essential, as well as the use of relevant reference standards, and the final wave documentation. More details on generation, analysis and documentation procedures, highlighting the same critical topics, are followed up in Chapter 6. Similar problems exist in numerical modeling (see Chapter 7).

4.1. Regular waves

Ideally, regular waves are periodic unidirectional progressive wave trains, with a single (monochromatic) basic harmonic.

Wave height and period. For most regular wave applications (see Table 4.1), the average wave height H and the average period T are of main interest. Amplitudes A, defined by $H/2$ or by crests A_C and troughs A_T, and the average steepness kA, are also used (k is the angular wave number). Ideally, properties should be constant throughout time and in space, but in physical generation there is always a certain level of variation. Time windows for analysis are selected on the basis of criteria such as minimum variations, minimum transient effects in the model test set-up, or minimum reflections from the beach or from walls. Normally a minimum of 10 wave cycles is selected. Parameters are defined by a time-domain (zero-crossing) approach or by a Fourier (harmonic) approach (mainly the basic harmonic). Simple RMS analysis of elevation records is also applied. Wave periods are referred to a global system or to a system following a vessel with a speed (the encounter frequency problem, relevant in seakeeping).

Non-linear effects. With increasing steepness kA, wave trains deviate from harmonic signals as crests A_C get higher and steeper and troughs A_T get flatter, as is well known for finite water depth conditions (see below), but significant also in deep water. They may be predicted from theory such as Stokes expansions or e.g. fully non-linear methods (Chapter

7). Non-linear regular wave characteristics are defined by components at higher harmonics or similar approaches. The asymmetric wave geometry, with increased crests and associated local steepness, can be essential in e.g. stability tests. To distinguish these 'real' non-linear effects in open-sea wave fields from 'parasitic' laboratory-defined ones, comparisons to theoretical/numerical reference models are helpful. 'Real' non-linearities also include set-down (reduction in mean elevation), higher-order instabilities such as Benjamin-Feir effects (Benjamin & Feir, 1967), dissipation and breaking. They should be documented whenever relevant, as they may introduce effects deviating from ideal laboratory conditions (see below).

Finite water depth. Wave generation in water of finite depths introduces additional effects relative to that in deep water. A summary is given here, while more details are described in Chapter 8. Dispersion is depth-dependent, with shorter wavelengths and reduced speed in decreased depths. This may lead to spatial variations due to refraction effects unless the bottom is perfectly horizontal and flat. Non-linear wave-wave interactions increase with reduced depth, with sharper peaks but also larger set-down effects and corresponding return currents. Shoaling may produce increases in wave heights, but limiting heights are reduced, as the breaking threshold is reduced. The wave field is in general subject to more dissipation, instabilities, and spatial variations. Non-linear 'parasitic' generation effects are also increased (see below). Various theoretical models have been developed, depending on depth.

Waves on currents. Theoretically, a perfectly steady current that is collinear with the waves slightly reduces the wave heights and increases the wavelength. Similarly, an opposing current increases the wave heights and reduces the wavelength. Normally the specified model waves are calibrated with the current on, so the changes in wave height are accounted for and embedded in the resulting wave field. Whether or not this practice is consistent with use of field data as specified, is a question brought forward (but left open) in the present work. Non-linear wave-current interaction effects influence the resulting hydrodynamic forces, such as wave drift damping (and corresponding modification in slow-drift excitation), wave-induced currents, wave kinematics and others. This is a field of continuous research. Waves generated at an angle with the current are subject to refraction effects. In physical current generation, there are also, to some extent, fluctuations in time and space, due to shear in the current field as well as to laboratory-defined sources. This may generate a spatially varying refraction pattern, and thereby, a limited useful area in space.

Deviations from ideal conditions. Ideally, regular wave modeling should generate a unidirectional periodic wave field with amplitude, period and direction constant throughout time and space. In practice, deviations from the ideal world are observed, for various reasons. Model testing procedures must take these into account, in one or several of the following ways: a) avoiding them, b) reducing them, c) documenting them and interpreting their effect on vessel responses (with or without the help from numerical modeling, see Chapter 7). Some critical phenomena are listed in the following.

Reflections from wave absorbers or walls can in some cases be avoided by choosing a proper location and time window combination. Perfect passive absorbers do not exist, but by optimal designs amplitude reflections down to the range 2% ÷ 5% can be obtained. See e.g. the 22nd ITTC**.** Active wave absorption (Naito, 1998, 1999; Schäffer & Klopman, 1997) is a promising technology in continuous development. When relevant, reflection should be measured and documented.

Non-linear low-frequency and high-frequency *'parasitic' free waves* generated at the wavemaker, in particular in finite and shallow water. They can be reduced by second-order generation techniques (Schäffer, 1996). Non-linear free wave generation can also occur, see e.g. Benjamin & Feir (1967): Lake et al. (1977), Stansberg (1993), Trulsen & Stansberg

(1999), eventually leading to disintegration, breaking and dissipation. over a shoal. *Spatial variations* due to refraction from bottom topography, and from current inhomogenities.. *Modulational instabilities* in time and space, after long propagation *Steepness-induced instabilities and breaking*, in particular in finite and shallow water, but also in deep water (Su, 1982)

Others. The choice of *model scale* may influence the characteristics of the modeled waves. Thus a very small scale normally introduces more wavelengths of propagation, and therefore more modulational instabilities and possible disintegration. Accuracy and repeatability is also a limiting factor to small scales. Scales down to 1:150 ÷ 1:200 have been reported, see e.g. Moxnes & Larsen (1998), but this seems to be presently at a lower limit for practical reasons (capillary waves represent no problem for waves longer than 20 ÷ 30 cm). *Repeatability* of generated waves is also essential. The *direction* of regular waves is normally along one of the two axes of the wave basin or tank, but with multiflap wavemakers oblique waves can be made, which leaves an additional parameter of the wave generation. Multiflap wavemakers can also produce *spatially focused* monochromatic (or periodic) waves, which needs specially designed specification and documentation. For special purposes, generation of *bichromatic* wave trains is made. Perfectly bichromatic waves are difficult to obtain unless the steepness is low or the propagated distance is short, due to higher-order instability effects even stronger than in regular waves (Trulsen & Stansberg, 2001). *Wave kinematics* is essential for small-volume structures and local phenomena around large-volume structures, and is sometimes requested for documentation.

4.2. Irregular waves

By 'irregular waves' we here mean waves generated with the purpose of reproducing specific (but not all) properties of a real random ocean wave field, with respect to time-varying amplitudes, spectral distribution, extremes, statistics, non-linearities, directional spreading etc. In most cases this means physical or numerical simulation of sample records of a random wave train, ideally assumed to be statistically stationary and homogenous in time and space, respectively, but it can also be a deterministic reproduction of specific events or models, including 'transient wave' generation.

Wave spectrum and related parameters. Sea states are most often specified by the short-term variance spectrum $S(f)$ or $S(\omega)$ of the elevation at a point (the omni-directional or 'point' spectrum), where f and ω are the frequency and the angular frequency respectively. Various spectral formulations are presented and discussed in Chapter 5 and Appendix A. Primary spectral parameters are the significant wave height H_s, defined as $H_{m0} = 4\sqrt{m_0}$, and a characteristic wave period, e.g. the peak period T_p or the zero-crossing period T_z defined from the spectrum as $T_2 = \sqrt{(m_0/m_2)}$. Here m_i is the i-th spectral moment. A shape description should also be given, such as the peakedness γ for the single-peaked JONSWAP model. The specified duration of random simulations is important, normally 1 hour for sea-keeping and 3 hours in offshore engineering. For a proper documentation of generated sea states, comparisons with target spectra are carried out, in addition to comparisons of parameters only.

Target spectra are smooth, while random realizations are often (not always) preferred generated with a 'natural' sampling scatter associated with finite records (Stansberg, 1989), although spectral smoothing or averaging reduces this effect. This must be taken into account in comparisons. Natural fluctuations consistent with the record length, and spectral smoothing are then expected. Other deviations from targets are also accepted within certain limits, but the documentation of actual spectra is essential, since resulting vessel responses may be sensitive to particular parts of the spectrum.

Bi-modal spectra, that is, wind sea plus swell, are now more frequently specified, as a result of better field data documentation, and may be essential for vessel responses. Normally it is specified as the sum of two monomodal spectra, or by an integrated formula, with a given set of parameters (see Appendix A). Each component is often modeled unidirectional, collinear or in different directions, while directional spreading is sometimes included (see below). Spectral documentation is important.

Sea state parameters based on time-domain analysis are also used, such as the zero-crossing parameters $H_{1/3}$ and T_z, standard deviations or RMS analysis, or other parameters. $H_{1/3}$ is an alternative estimate of the significant wave height, and for a linear wave train it is slightly (2%÷5%) lower than the spectrum-based H_{m0}, while T_z is in practice slightly longer than the spectral estimate T_2. For non-linear waves, in particular in shallow water (Chapter 8), the opposite may be the case. A general description of sea state parameters is given in IAHR (1987).

Directional spreading. In the past, most model tests have been specified with unidirectional waves. There are several reasons for this. Only a few facilities have been able to model multidirectional waves; field data documentation has been lacking or is uncertain; and the effect on structural and vessel responses is still being investigated as it has complex aspects. However, more and more facilities and documentations are now becoming available, methods for generation and documentation are improved, and sensitivity studies so far have shown significant effects in various cases. An overview is found in Mansard (1997). Its use is therefore expected to increase in the future. Directional spreading is specified by simple monomodal parametric models for the directional spectrum $D(\theta)$ (one for each peak in a bimodal sea state), see Chapter 5 and Appendix A. Documentation, which is not always done in standard model tests – probably because it is a more complex process than for point spectra, is done either by comparison of estimated against target spectra or of spreading parameters such as spreading bandwidth (see Chapter 6). In cases with two unidirectional spectra specified from different directions, a documentation of the generated directions is recommended.

Non-linear effects and extremes. Critical and extreme vessel or structural responses are often connected with non-linear and/or extreme wave conditions. When this is important, specific wave properties are considered, and reference is made to theoretical models or standards. At present, practical reference models for random waves are based either on linear or on second-order theory, while higher-order or fully non-linear models are complex and still in development (Chapter 7). There are several different wave characteristics to be addressed:

Non-Gaussian statistics: In random elevation records, footprints of non-linearities are observed in systematic deviations from Gaussian statistics, e.g. through the normalized third- and fourth-order statistical moments *skewness and kurtosis*. Their expected values in a Gaussian sea are 0.0 and 3.0, respectively, but statistical scatter must be expected in short records, especially for the kurtosis. *Probability distributions* for the elevation itself or for individual w*ave and crest heights* are also helpful, especially when compared to linear models (Gaussian for elevation, Rayleigh for peaks), or, in more sophisticated analyses, to non-linear models. Experience has shown that second-order models fit well with field data (Forristall, 1998), and they also compare reasonably well with or are slightly under-predicting laboratory observations, see e.g. Stansberg, 2000a). Under very special conditions, larger deviations may also be observed (Stansberg, 2000b), explained by the development of higher-order modulational instabilities (see also below and Chapter 7).

Extremes and rare events: Expected extremes in a random record are commonly predicted from the simple Rayleigh model, valid for linear waves. In real waves, however, higher crest extremes are expected and observed, as in regular waves, and a second-order model is a more proper standard (Forristall, 1998). Extreme peak-to-peak wave heights, however, are quite close to Rayleigh predictions. Furthermore, sample extremes are subject to statistical sampling scatter (Stansberg, 1998b), so directly observed extremes in a finite record must be interpreted with care. (In direct and deterministic comparison with numerical reconstructions, however, this problem is avoided). Improved interpretation and estimation can be made in combination with statistical analysis (see above), or with very long records. Wave modeling is sometimes specified with certain criteria for extremes.

Recently, there has been a growing interest in possible higher-order mechanisms leading to particularly high extremes ("rogue waves"), based on real sea observations as well as theoretical and experimental findings. Descriptions of various approaches have been presented in the Proceedings of the *Rogue Waves 2000 Workshop* (Olagnon & Athanassoulis, 2002). It was also addressed by ISSC (2000). This is, however, still a field in continuous development, with no consensus and reference standards established yet.

Transient waves: Model testing with single wave groups of moderate steepness is a frequently applied technique for efficient estimation of linear vessel RAO's, and at the same time avoiding possible reflections in a wave tank. Single wave events with high steepness is a related method, but then with the purpose to investigate non-linear responses (or simply the wave properties itself) in a given, non-linear wave. Combination of transient waves with random wave simulation has also been suggested (Clauss & Steinhagen, 2000; Kriebel & Alsina, 2000)

The specification of the actual wave event to be reproduced must be made according to given criteria, e.g. referred to one or more of its parameters (such as wave height, crest height, asymmetry, local geometry or others). It can also simply be a reproduction a given event (which may be picked out from a longer random wave simulation in detail). Procedures for such criteria must be made based on available information on extreme waves relevant for the actual application. A special reference model is the NewWave, based on statistical criteria (Tromans et al., 1991). The transient wave method is time efficient, especially if rare events are considered. In particular, the combination of this with non-linear numerical modeling of the same problem, seems to be promising. An overview description of the technique was given at the 22nd ITTC, while a more comprehensive presentation has been given by Clauss (1999).

Wave breaking and spatial geometry: Certain vessel and structural responses are sensitive to the wave geometry and possible breaking, such as in stability, ringing, green sea and impact force problems. In most *random* wave simulations, these are not particular items of the specification, but too much breaking is normally avoided due to uncertainties introduced in the wave loading (scale effects; different loading mechanisms; instabilities). The geometry of random extreme waves is then considered a result of (non-linear) stochastic combinations. Wave geometry effects on green sea problems have been studied by Drake (2001). In deep water, breaking is most frequent within 1-2 wavelengths from the wavemaker, and this area is often avoided as an 'unstable' area. In finite water, it is depth-determined and often concentrated at a certain area of the wave field, to be taken into account in planning. For *transient* extreme wave testing, the individual wave geometry, such as local steepness properties, and possible breaking may be particular properties to be taken into account in the specification and documentation. See also the 22nd ITTC Report. Comparisons to fully non-linear numerical models are expected to become more important in the future.

<u>Wave grouping</u>. The groupiness in a random record (see e.g. Mansard & Sand, 1994), which can be essential for e.g. slow-drift, stability and green sea problems, is regularly formulated through the low-frequency *group spectrum* (or energy envelope spectrum). Its expected shape is given simply as the autoconvolution of the wave spectrum, for linear waves. It is a helpful reference for documenta-

tion. Systematic deviations indicate higher-order non-linearities which may lead to non-linear extremes (Stansberg, 2002a). However, group spectra show a significant natural sampling scatter, to be distinguished from 'real' physical effects.

Finite depth. Spectra are affected by the bottom depth, through shoaling, refraction, breaking and other dissipation, and are therefore location dependent. Maximum possible wave heights decrease with decreasing depth. Non-linear and Non-Gaussian effects are stronger than in deep water, although sharper crests are to some extent compensated by increased group-induced long waves (set-down variations), and depth-induced breaking reduces the crests. More details are given in Chapter 8.

Waves on current. The significant wave height is reduced in a collinear current, and increased in an opposed current. Also the spectral shape is influenced. These effects are usually compensated for in laboratory calibration. Directional spectra are affected by current-induced refraction.

Deviations from ideal conditions. Special considerations for irregular waves are given in the following. Spectra may change downstream a wave tank due to higher-order instabilities, breaking and dissipation (Stansberg, 1993, 2000). This may also lead to modified statistical properties, especially in uni-directional waves, with particularly high extremes in special cases. Thus it is essential to calibrate the waves at the location of interest.

Further aspects of finite depth effects, waves on current, deviations from ideal conditions, and other special topics, common for regular and irregular waves, have been described previously for the regular waves.

Table 4.1 Relevant parameters, regular waves (A = important; b = may be relevant).

		H	T	kA	$\sum f_i$	f_{enc}	$\vec{V}$	S_t	S_s	N
		Wave height	Wave period	Steepness	Harmonic analysis	Encounter frequency	Kinematics	Stability in time	Stability in space	Number of wave cycles
SEAKEEPING	• Motion RAO • Green Sea • Impact loads • Speed loss	A	A	A	A	A		A	A	A
STABILITY / SAFETY	• Ship motions	A	A	A		A		A	b	A
FIXED SLENDER STRUCTURES	• Force RAO • Nonlinear force (inertia & drag) • Run-up • VIV	A	A	A	A		A	A		A
STATIONARY FLOATING SYSTEMS	• Response RAO • Nonlinear motions (HF & LF) • Damping • Viscous effects • Excit. QTF • Mooring forces	A	A	A	A		b	A		A

Table 4.2 Relevant parameters, irregular & transient waves (A = important; b = may be relevant).

		H_s Significant wave height	T_p T_z Spectral peak and mean zero-crossing period	$S(f)$ Scalar spectrum	$D(f)$ Directional spectrum	H_{max} A_{max} Extremes (wave and crest heights)	$\eta(t)$ Statistics of elevation and peaks	Wave group analysis	*fenc* Encounter frequency	Set-down	$\vec{V}$ Kinematics	$\eta(x)$ Single wave geometry	S_t Stability in time (stationarity)	S_s Stability in space (homogenity)	T_{rec} Record duration
SEAKEEPING	• Motion RAO • Green Sea • Impact loads • Speed loss	A	A	A	b	b	A	b	A		b		A	A	A
STABILITY / SAFETY	• Ship motions	A	A	b	b	A	A	A	A		b	A	A	A	b
FIXED SLENDER STRUCTURES	• Force RAO • Nonlinear force (inertia & drag) • Run-up • VIV	A	A	A	b	b	b	b			A	b	A		A
STATIONARY FLOATING SYSTEMS	• Response RAO • Nonlinear motions (HF & LF) • Damping • Viscous effects • Excit. QTF • Mooring forces • Green sea • Run-up • Impact	A	A	A	b	A	A	A		b	b		A		A

Table 4.3 Relevant parameters, special wave conditions (A = important; b = may be relevant).

		Waves + current:		**Finite & shallow water:**
		Current velocity	Relative direction	Depth
SEAKEEPING	• Motion RAO • Green Sea • Impact loads • Speed loss	b	b	b
STABILITY / SAFETY	• Ship motions	A	A	b
FIXED SLENDER STRUCTURES	• Force RAO • Nonlinear force (inertia & drag) • Run-up • VIV	A	A	A
STATIONARY FLOATING SYSTEMS	• Response RAO • Nonlinear motions (HF & LF) • Damping • Viscous effects • Excit. QTF • Mooring forces	A	A	A

5. SPECTRAL FORMULATIONS

In many cases, the essential spectral characteristics of waves offshore can be captured by a standard formulation that is defined by a small number of independent parameters. Several such models have been proposed, and many of them have several features in common. However, none is appropriate for all situations. They are mostly simple formulas that have been found to fit specific measured field (and in some cases, laboratory) data, and are consistent with what is known about the fundamentals of irregular waves. Details of many such spectral forms are set out in Appendix A (point spectra only).

Many widely-used models for the spectrum of waves measured at a point (without regard to wave direction) are of the form

$$S(f) = \frac{A}{f^5} \exp(-B/f^4) \qquad (1)$$

(Bretschneider, 1959) where f is the frequency and A and B are constants. Among this type are those referred to by the names of Pierson & Moskowitz (one- and two-parameter forms), ISSC, ITTC, and Liu. These presentations differ only with respect to the parameters that are used in determining A and B, as shown in Table 5.1. They are formally identical.

Table 5.1 Parameters used to evaluate the constants of the Bretschneider spectral form.

Spectrum	***A* and *B* defined n terms of**
One-parameter Pierson-Moskowitz	Significant wave height or windspeed or peak period
Two-parameter Pierson-Moskowitz	Significant wave height and peak period
ISSC	Significant wave height and mean period
ITTC	Significant wave height and one of the following energy period, peak period, mean period, zero-crossing period
Liu	Windspeed and fetch

Other spectra include those related to the basic Bretschneider form, for cases where there is a limited fetch (JONSWAP), a finite water depth (TMA), a concentration of wave energy at two different frequency ranges (e.g. swell and storm waves: Ochi & Hubble; Guedes Soares, 1984; Torsethaugen, 1993), or a combination of a known wind speed and limited fetch (Mitsuyasu, 1972). In a third class of spectra are those represented by simple formulas that have been used merely to represent idealised conditions (Scott, Gaussian). Sometimes a broad banded spectrum of some specific shape is used to obtain RAOs (pink noise).

Details of many of these spectra are tabulated in Appendix A, which includes formulas for estimating frequencies that correspond to certain energy thresholds, and an explicit approximation for the depth function in the TMA spectrum.

There is continuing discussion in the literature on the question of whether, at high frequencies, wave spectral density is proportional to f^{-4} rather than f^{-5} (as in those forms related to the Bretschneider spectrum). The latter is consistent with an analysis by Phillips (1958) of the conditions in which there is a balance at a given frequency between the rate at which energy is gained from the wind and the rate at which it is lost by wave breaking and by transfer to other frequencies. It is also in excellent agreement with many observations (see e.g. Hogben & Tucker, 1994). On the other hand, the f^{-4} relationship is a good fit to some parts of the wave spectrum in other data, as described by Toba (1973) and Forristall (1981) among others. Further discussions on this point are found in Ochi (1998); Tucker & Pitt (2001).

For modelling purposes, the directional characteristics of waves offshore are sometimes assumed to be uncoupled from their spectral properties, and then the spectrum of waves travelling within a given range of headings is taken to be some proportion of that measured at a point. On this basis, the directional spectrum is of the form

$$S(f,\theta) = S(f)\ G(\theta), \tag{2}$$

where the spreading function G depends only on the direction θ. Its most common form is

$$G(\theta) = F(s)\ cos^{2s}\ \tfrac{1}{2}(\theta - \theta_1), \tag{3}$$

where θ_1 is the predominant wave direction, and s is an index that determines the width of the directional spread. (In other forms of $G(\theta)$, the power $2s$ is replaced by s, or the argument of the cosine may omit the factor 1/2. In another approach it can be expressed just in terms of its angular harmonics.) See e.g. Frigaard et al. (1997) for further details. In the present case the function

$$F(s) = \frac{2^{2s-1}}{\pi}\,\frac{\Gamma^2(s+1)}{\Gamma(2s+1)}, \tag{4}$$

ensures that the total variance of the directional spectrum $S(f,\theta)$ is the same as that of the point spectrum $S(f)$.

It is more realistic, however, to assume that the directional spread of the waves is not the same at all frequencies. In this case it is generally found that s reaches a maximum at a frequency slightly above that corresponding to the peak of the point spectrum. Models for frequency-dependent spreading functions are described in Mitsuyasu et al. (1975), and Hasselmann et al. (1980).

6. GENERATION TECHNIQUES

Through comparative research in the 17th ITTC, an extensive discussion was made on long-crested irregular wave generation, and most of that is still relevant. The contributors discussed the parameters to be reviewed for quality control, non-linear effects on mean period, and influence of propagation distance. They also discussed appropriate sampling rates for wave analysis, and the minimum number of waves for statistically stable data acquisition. Other issues included spectral and statistical methods for time series analysis.

Since the 17th ITTC, there has not been much discussion on wave generation procedures, even though many member institutes have developed their own wave generation methods adopting new digital technologies and directional wave technologies.

However, in the last (22nd) ITTC, an overview and brief discussion was given for regular wave generation, irregular 2D-wave generation, 3D-wave generation, and transient wave generation techniques. Special emphasis were made for 2nd order wave generation, wave group generation and transient wave group generation techniques.

In the present Chapter, critical items in wave generation are reviewed in the light of the quality of the generated waves. The presentation should be seen in connection with the definition of critical parameters and characteristics in Chapter 4. Regular waves are considered first, while most of the discussion is on irregular waves following next. For irregular waves, uni-directional (long-crested) as well as multi-directional (short-crested) wave modelling is included. Furthermore, stochastic as well as deterministic (transient) waves are considered. Nowadays most institutes prefer to use stochastic model waves, but the demand for extreme model waves is increasing in connection with highly non-linear responses in so called freak waves; transient wave testing is then one alternative.

In most cases, the scale of model wave is determined according to the scale of the model. But sometimes the wave generator's range of wave heights and bandwidth determine the upper limit of the model scale especially for higher met-ocean conditions.

6.1. Regular wave generation

Regular wave tests are performed mainly to get RAOs for linear responses, but are sometimes used to help understanding of nonlinear phenomena, and to confirm numerical simulation under idealized conditions.

Hence the quality of generated regular waves should be carefully monitored, because their quality degradation may occur quickly during propagation (Benjamin & Feir, 1967; Stansberg, 1993). Also, more attention has to be paid to the passive or active wave absorption of the beach and other boundaries. Active absorption is addressed in connection with directional wave generation later in this chapter. For the generation of steep regular waves, second order generation techniques for irregular waves (Schäffer, 1996) can be used to suppress unwanted parasitic waves such as sub- or super-harmonics due to non-linear dispersion. Depending upon the application, documentation of possible deviations from ideal conditions such as reflections should be made made available from the tests (see Chapter 4 and the 22nd ITTC Report on Environmental Modeling). In the wave analysis, stability in time should also be documented, as well as stability in space whenever relevant.

Oblique regular waves are sometimes used in a basin with a multi-directional wave generator. This will be discussed in a sub-section on directional wave generation.

6.2. Irregular wave generation

<u>Unidirectional wave generation</u>. Unidirectional (or long-crested, 2D) irregular waves are frequently used in most model basins not only because this represents a real sea-state in a very simple form, but also because it usually gives a worst case for loadings and responses compared to short-crested (directional) seas. It is also easier to define a sea state in a unique manner.

In the generation of 2D irregular waves, it is important to maintain the randomness that will prevent unrealistic repetition of the waves. Also, careful attention should be given to the effects of the frequency range covered by the servo system. The test duration and the number of frequency components adopted are also important if the proper natural statistics of the wave field are to be reproduced. Wave reflection from the beach and diffraction by the basin wall should be monitored carefully.

Generation of oblique long-crested irregular waves by multi-directional wave generators is now frequently used in many basins, and this will be discussed in a sub-section on directional wave generation.

In the generation procedure, excessive acceleration, velocity and displacement of the wave board motion should be checked and modification of the signal by some band-pass filters should be made, with a knowledge of the capability of the machine. This mechanical limitation leads to frequency truncation of the given spectrum. The size of time step Δt should be much less than the period of the shortest wave component and is usually determined by the controller's clock capability.

No recommended procedure for determining the upper and lower cut-off frequencies has been agreed. One has to minimize the effect of this truncation by carefully selecting the model scale for a given spectrum and wave machine. High frequency truncation lowers the mean period, reduces the bandwidth and is known to affect the slow drift motion due to wave-wave interaction (due to difference frequency effects). Low frequency truncation is said to be related to asymmetric wave profiles for high amplitude non-linear waves.

Increasing the number of component frequencies increases the frequency resolution and improves the statistical representation of the waves, as discussed in the 22nd ITTC. The longer the duration of wave generation (determined by the nature of the model tests), the more frequency component are needed. The specified duration of random simulations is important, normally 3 hours for modeling a full storm. This is most often used in offshore engineering tests. It can be changed depending on the phenomena the test is focusing at, however it must be long enough to realize statistical properties if non-linearities and extremes are to be studied. Frequently, even longer durations are achieved by running several independent realizations with different random seed numbers for generating the phases. For seakeeping tests, at least 100÷200 waves has traditionally been used (typically 0.5÷1 hour), which is often defined as satisfactory if linear effects only are considered.

As in the case of regular waves, the quality of irregular waves generated in a tank varies in space and in time. For higher non-linear sea-states the wave height can be reduced by 10% ÷ 15% at a distance of 20 representative wave length from the wave board (Stansberg, 2000). Other parameters like mean slope, spectral shape, extremes, skewness, and kurtosis are also spatially varied. Pre-calibration of wave conditions at the test location of an offshore structure model is therefore needed. Documentation of stability in space, reflections etc. is also recommended when relevant. Methods for reduction of reflections are described in the 22nd ITTC and also addressed later in this section in connection with directional generation.

Wave generation techniques accounting for parasitic second-order effects are proposed by several authors, such as Schäffer (1996). Schlurmann et al. (2000) used Schäffer's technique and a back scattering method to generate a 2nd order wave control signal for his study of freak wave generation.

For tests in long-crested irregular waves, documentation is in general needed on the spectral shape, minimum and maximum frequencies, significant wave height, peak period, zero up-crossing period, band width, skewness, kurtosis, and water depth. Comparison of spectral shape with the target spectrum is the best way of assessing the quality of the waves, but there are no given rules for this. Figure 6.1 shows a typical example of laboratory documentation.

<u>Directional wave generation</u>. Many basins now use multi-directional wave generators to achieve more realistic wave environments. Mansard et al. (1995) summarized an extensive survey results by IAHR for comparison of various existing multi-directional wave generators owned by 40 institutes. Wave generators in this case usually consist of many small wave boards, which can be controlled independently by electric or electric-hydraulic actuators. Due to the effects of the Biesel limit on the size of the wave board and reflection from the wall, wave characteristics in the test region need to be carefully determined.

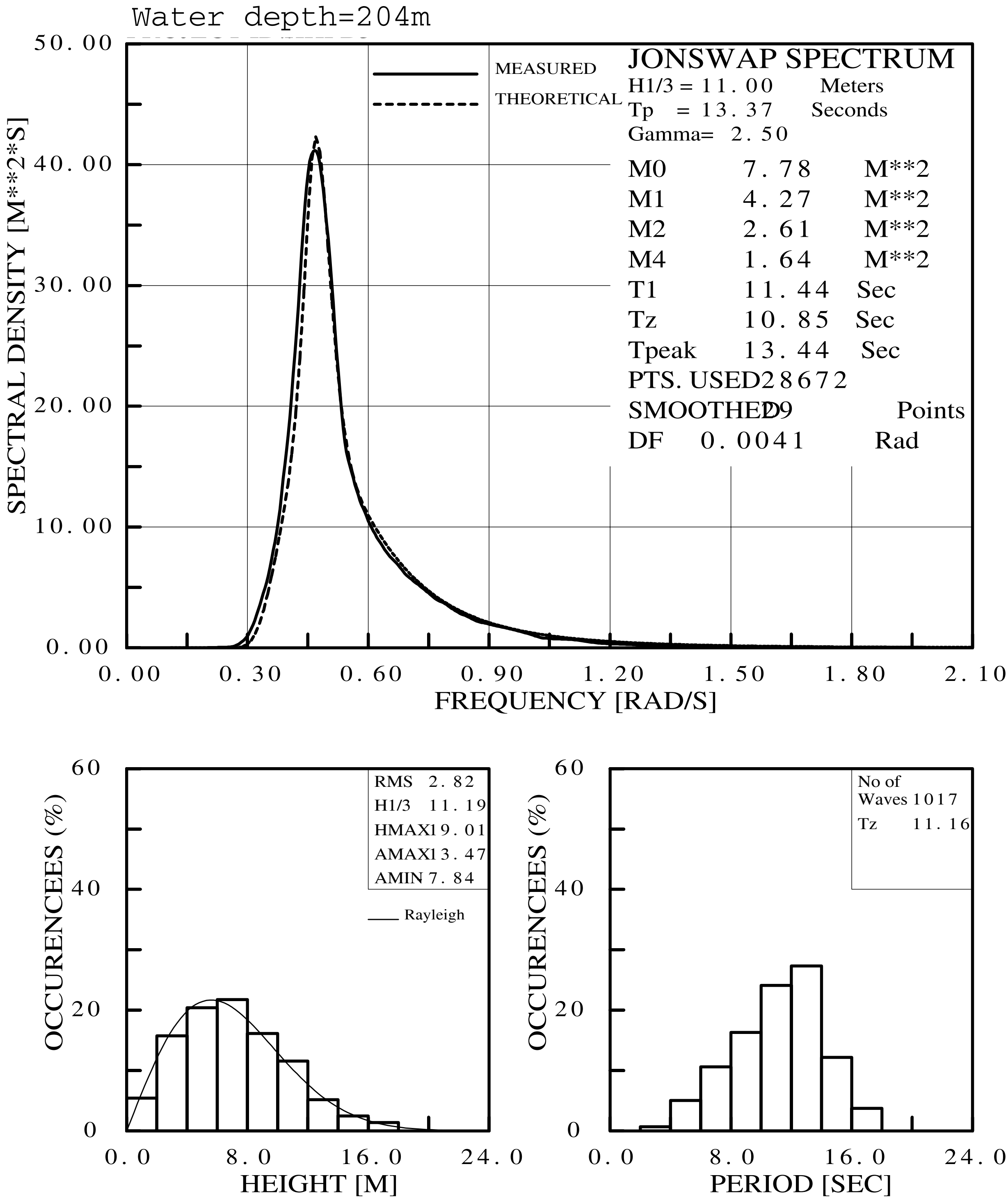


Figure 6.1 Sample of Documentation of Wave Characteristics.

The directional nature of the real sea is characterized by a directional wave spectrum which is a joint distribution function of wave frequency and direction. This is usually represented as the product of the point spectrum and a directional spreading function, essentially because it is difficult to handle the joint distribution function directly.

Modelling directional spectra in the laboratory is generally associated with a significant random scatter, especially in the finer features of the measurements. This reflects features of real sea data, reflecting natural statistical scatter Stansberg (1998a). Therefore, a robust description of the directional sea conditions is often restricted to a few parameters only, such as mean direction, directional spread, and a simple shape parameter that expresses the bimodality (such as skewness and kurtosis, see Kuik et al., 1988; Stansberg, 2002b), or simplified smooth parametric models such as the $\cos 2s(\theta)$-model.

More detailed representations are sometimes obtained by e.g. the maximum entropy method, but it should be remembered that the real physical information which can be obtained is basically limited by the finite record length and the area of the measuring system. In any case, the resulting estimates may be influenced by the actual measuring system and analysis, and documentation of the procedure actually applied is therefore an essential part of the results.

Various methods have been proposed to measure and analyze directional wave spectra for either field or basin measurements. There are three widely used methods: wave gauges in a wave probe array, a heave-pitch-roll gauge, and a 2- or 3-axis wave velocity gauge. Analysis methods differ according to the type of gauge, but they can be categorized as a parametric model, a maximum likelihood method, a maximum entropy method, a Bayesian directional method, Fourier series methods, etc.

A working group organized by IAHR was formed in 1994 to study multidirectional waves. The research results were reported at an IAHR seminar (Mansard, 1997). Some of the papers are referred in the following.

A comparison of various analysis methods for multidirectional waves was given by Hawkes et al. (1997). They compared results independently analyzed by participating laboratories with various analysis schemes. They investigated the agreement between analyzed data and target values mainly in terms of directional parameters such as mean direction, spread, reflection coefficient and wave energy against direction. Benoit et al. (1997) reviewed directional analysis methods for linear waves in open water conditions. They concluded that the efficiency of the analysis method depends on the type of measuring device and the properties of directional wavefields.

Miles et al. (1997) compared multidirectional wave characteristics generated in six different laboratory basins so as to examine the variability due to different wave synthesis and generation methods. They found that in general the degree of variability is acceptable in view of many factors involved in the different wave synthesis and generation methods, though larger deviations occurred in the outer regions of the basins. The synthesization techniques of directional waves are also discussed in the 22nd ITTC.

<u>Active wave absorption</u>. Schäffer & Klopman (1997) reviewed multidirectional active wave absorption methods and focused on hydrodynamic feedback and absorption control mechanisms. They considered 2-D systems in wave flumes, quasi 3-D systems for multidirectional waves consisting of an array of independent flume systems, and fully 3-D systems considering a coupling between neighboring feedback signals. Naito (1998) and Naito et al. (1999) proposed an arbitrary shaped multi-directional wave generator along the whole basin using active wave absorption methods.

<u>Oblique wave generation</u>. In a numerical study Ishida & Watanabe (1985) proposed a method for minimizing the effect of wave-

board size by gradually changing the stroke of the motion near the ends of wave generators.

Various methods to improve the generation of oblique regular waves by using wall reflections also have been presented by Funke & Miles (1987), Gilbert & Huntington (1991), Benoit (1995), Hirayama (1997), Maron (1999), Yang et al. (1997, 2001), and Boudet & Perois (2001). These efforts result in a large increase in the useable tank area.

<u>Non-Gaussian properties and extremes</u>. A documentation of deviations from Gaussian distribution of elevations, or from the Rayleigh model for peaks, is commonly made for stochastic (random) seas. Reference models can also be second-order, and this is now more or less established as a robust model for engineering use. It is also important, however, to take into account the significant statistical scatter expected (and observed) for sample extremes, and methods for more robust extreme value estimations are frequently applied. This includes use of e.g. Weibull-tail fitting estimations from probability distributions, and also sometimes the running of additional realizations to increase the number of independent cycles.

Non-linear effects may vary in space, especially over large distances (Stansberg, 2000a), and it is essential to document them at the proper location.

Comparison with non-linear numerical models is often helpful, and is addressed in Chapter 6. The numerical and physical modeling of extreme waves, with the emphasis on second-order as well as higher-order models, was extensively discussed in the *Rogue Waves 2000 Workshop* (Olagnon & Athanassoulis, 2001). Generation techniques include stochastic (random) simulation as well as deterministic event reproduction (transient wave generation).

For random simulations, linear input signals are most often used, and non-linearities appear in the waves naturally. Non-linear disturbances from the wave paddle (‘parasitic waves’), that are most pronounced in finite water depth, can be reduced by a second-order generation method (Schäffer, 1996).

<u>Transient Wave Generation</u>. All transient wave techniques require a so-called concentration point or target point where all wave components are superimposed with specified phase differences. In principle, it is not necessary to assume zero phase differences if all the information of the wave components (including their phase information) at the target point is known. For example, from a real sea storm wave train at a certain target point, which can be reproduced by superposing a number of wave components with specific phases, a wavemaker control signal can be generated by using complex Fourier transforms and a linear or non-linear dispersion relationship.

Tromans & Suastika (1998) deal with the inverse problem of estimating the wave history that will produce an extreme response on a given structure. Zou & Kim (2000) consider the possibility of reproducing some non-linear transient waves such as strongly asymmetric wave profiles. However, there is no systematic approach for designing a deterministic extreme wave train directly from measured storm data yet, though the approach followed by Chaplin (1997) has been used to generate complex wave sequences in 2D. Most transient wave studies aim to achieve zero phase differences, and component amplitudes from a specific wave spectrum, at a concentration point.

Clauss (1999) described various applications of using transient wave packet methods for seakeeping and offshore tests. Kriebel & Alsina (2000), Clauss & Steinhagen (2000), and Hudspeth et al. (1999) proposed methods of embedding wave packets into a background random wave series while maintaining the desired spectrum systematically.

In laboratory studies Kway et al. (1998) generated breaking waves using wave packets with three different component distribution, i.e., constant amplitude components, constant steepness components and components following the Pierson-Moskowitz distribution.

Wave breaking can be generated by wave focusing of not only different frequency waves but also different directional waves. However, there is a general lack of research on three-dimensional wave breaking because of the complex nature of the process that has so far hampered both numerical and experimental research in this area. A few key papers include those of Su (1982), She et al. (1994, 1997), and Johannessen (1997). Their results showed that the incipient breaking wave height, crest elevation, crest-front steepness and vertical asymmetry factors are strong functions of the angular spreading. Generally, the greater the spreading angle, the bigger the breaker. Also, She et al. (1997) showed that increasing the angular spreading had the effect of making the velocities within the extreme waves larger. In addition, Johannessen (1997) showed that the introduction of wave directionality is to reduce non-linear wave interaction significantly. The non-linear crest height can be reduced up to 40% as a direct result of wave field directionality.

Hong et al. (2001) proposed an effective scheme for the generation of directional breaking waves and examined the influence of associated parameters, such as the directional range, frequency width and center frequency. However, the generation of transient directional waves is still a matter of considerable effort and interest.

In most laboratories, deterministic extreme wave studies have been made as 2-dimensional phenomena, even though there is good evidence that the 3-dimensional contribution to the formation of extremes wave in real sea conditions may in some cases be important.

Wave grouping. Random waves are most often generated in the laboratory without any particular attention to wave groups. Groups occur as a natural result from stochastic combinations of harmonic components, with narrow spectra leading to long groups and broad spectra leading to short groups. There are methods for controlling the groupiness in a random record, but one should remember that this affects the 'randomness' of the record.

Documentation of groupiness is normally made by means of 'group spectra' (the spectrum of the energy envelope, ref. e.g. the Hilbert transform technique, Medina & Hudspeth, 1988), compared to the expected spectrum assuming a linear wave model. Systematic deviations, which must be distinguished from the significant random scatter present in group spectra, are connected with high kurtosis values and indicate higher-order non-linear effects (Stansberg, 2002a).

7. NUMERICAL METHODS AND INTERACTION WITH MODEL TESTS

7.1. General overview

The increasing availability of powerful computational resources has recently attracted a large amount of research in the field of the simulation of waves and wave-structures interaction processes. CFD codes developed in this context are aimed to be used either as direct design tools or alternatively as design tools (preprocessing) of complex tests in physical basins. It is well recognized that the role of numerical simulations in the engineering design process is constantly increasing since the 'virtual test' is conducted in controlled environmental conditions and the amount of information available is orders of magnitude higher than any complex physical test. Pressure, tangential stress and velocity field (primitive quantities) are typical outputs that can be post-processed easily leading to more familiar integral parameters (forces, hydrodynamic coefficients, …).

At the same time the increasing high frequency storage capability of data acquisition systems has led to the growing use of PIV and LDV in experiments. The nature of the results of these techniques (Lagrangian or Eulerian velocity fields) is now closer to that of CFD than to those of 'traditional' experiments. Ultimately they can provide turbulence characteristics from statistical properties of the measured flow. In this new experimental perspective, numerical simulations can play a fundamental role for cross comparison.

Numerical Wave Tanks (NWT) have also become a powerful research tool in studying wave-wave and wave-structure interactions. The challenging goal of making these computational procedures part of the design process – or part of the design and interpretation of model tests – has been addressed over the last two decades.

This Chapter provides a brief review of issues related to the use of numerical models for the interpretation of experimental results in physical wave basins.

<u>Parasitic effects in wave tanks</u>. Recently Molin (2001) has given a clear description of the interaction between numerical and physical wave tanks in the design process. In his review, mainly derived from a French research project (1996), the basic problems arising in the generation of quality waves in a numerical or physical wave tank are described, and the discrepancies between analytical, numerical and experimental results in the time and frequency domain are analysed. "…As a matter of fact, even though it may look simple, generating a Stokes regular wave in a tank is impossible: as the wave maker gets started, a transient stage ensues when all natural modes of the tank participate; the long modes damp out slowly and last throughout the test and beyond; as the wave front travels down the tank a return current is established; if no proper control is applied to the wave maker motion, free waves at harmonics of the fundamental wave frequency are emitted; reflections occur from the beach, back to the wave-maker, etc…". It is observed that most discrepancies between numerical and experimental results appear in transient phenomena: at the start-up of the wave-maker, at the wave front, in the presence of wave packets. Moreover physical and numerical beaches behave in different ways. Both methods suffer from seiching modes of the tank (long undamped waves) generated at the start-up of the wavemaker, from the presence of the return current (Skjelbreia et al., 1989) and of the reflected waves.

These effects should be considered carefully in attempts to match measured or computed kinematics in closed basins to analytical or theoretical models in unrestricted waters.

In any case, the availability of powerful numerical simulations of environments that are 'controlled' (at least in terms of the incident waves, reflections, non-linearities) and free from experimental uncertainties, makes the analysis of complex physical phenomena from tests easier. This applies particularly to non-linear effects (free and tied waves) derived from wave generation, wave-wave interaction, wave-body interaction; it relates also to side wall and beach reflection effects, and in general undesired influences of the limited fluid domain of a basin (such as seiching modes, multiple reflections, mean bottom return current).

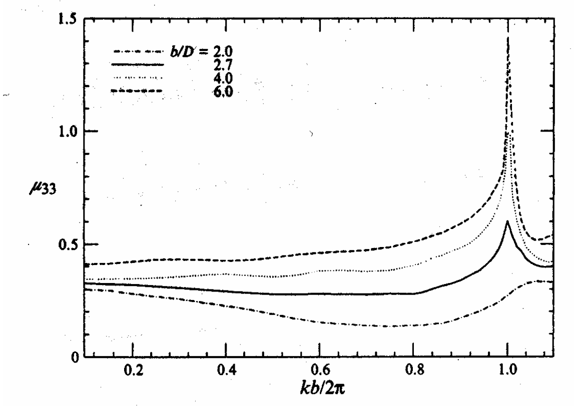
<u>Non-linear effects</u>. In the field of non-linear effects, Longuet-Higgins et al. (1976) pioneered the Mixed Eulerian Lagrangian approach for the simulation of unsteady periodic free surface flows in inviscid fluids. Since then many other applications and development of the method have been presented.

In this context, and linked to the annual ISOPE Conference, the Numerical Wave Tank Group was established in 1995 under the leadership of Professor C.H. Kim (Texas A&M Univ.) and presently Professor S. Grilli (Rhode Island Univ.). At the start, Kim (1995) presented a review on the NWT approach. Since then, each year a benchmark test has been proposed to software developers for direct cross checking. Generation, propagation, absorption, radiation, diffraction and wave drift processes with fully non-linear free surface in viscous or inviscid fluid have been the main subjects of these tests. The results of the benchmarks proposed can be found in the proceedings of the ISOPE Conference, under the NWT sessions.

Clement et al. (1999) presented some numerical results on self and dual wave-wave interaction. In the case of 2D wave packets running in opposite directions the phase speed is changed due to non-linear interactions.

Trulsen & Dysthe (1997) analysed by a modified non-linear Schroedinger equation the conservative evolution of weakly non-linear narrow-banded gravity waves in deep water in wide wave tanks. From their analysis it is seen that in two dimensions no permanent shift of the peak of the spectrum is observed. In three dimensions on the other hand, with oblique side band perturbations, the peak is permanently downshifted, and there appear standing waves across the tank. Experimental evidence of this has been indicated in Trulsen & Stansberg (1999).

Yao et al. (1994) studied the behaviour of the amplitude of waves generated by heaving wavemakers of conical shape with different elliptical cross sections placed with their axis in the middle of a narrow tank. The tank width is varied between 2.7 and 6 times the cone diameter. They have shown that the amplitude of the radiated wave disappears for a circular cross section at the first cut-off frequency corresponding to the B-mode and that this behaviour is insensitive of the tank width. It is also shown that in the case of an elliptical cross section with its larger axis in the direction of the tank, the radiated wave amplitude disappears at a lower frequency. The comparison with experimental data is extremely good. These phenomena are closely related to the hydrodynamic coefficients of the heaving cone, added mass (Figure 7.1, top) and wave damping (Figure 7.1, bottom) that exhibit a large peak and a strong discontinuity respectively at the cut-off frequency. This is magnified in a wide tank. Finally it is shown experimentally and numerically that operating at a frequency close to the first cut-off frequency results in a continuous intermittent propagation of sloshing wave groups downtank. The speed of these groups behaves linearly with the stroke of the heaving cone (Figure 7.2). Below a given threshold wave are entirely suppressed. Moreover the observed deformation of the shape of the sloshing groups downtank was related to the small fluctuations of the width of the tank. See also Wu et al. (2000) mentioned in subsection 7.2.



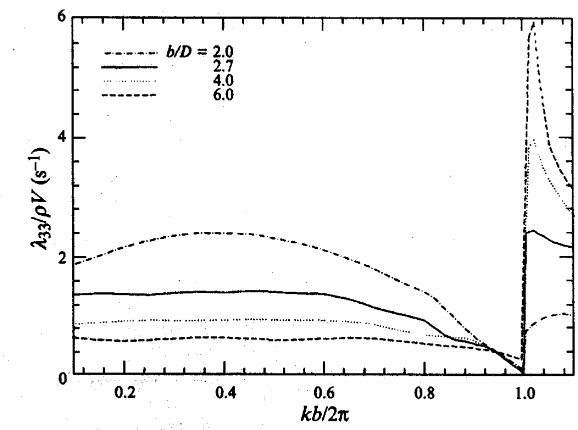


Figure 7.1 Non-dimensional added mass (top) and damping (bottom) coefficients as functions of $kb/2\pi$ (b = tank width, D = cone diameter) for a half-cone wavemaker with various tank widths (Yao et al., 1994).

Instabilities of a wave train. Yuen & Lake (1980) reviewed the instabilities of waves in deep water, which was also observed and discussed in e.g. Benjamin & Feir (1967) and Stansberg (1993). In particular they highlighted the work of Crawford et al. (1978) on the dependence of the unstable modulation frequency Ω_{MAX} on the carrier wave steepness (Fig. 7.3). Their study was carried out by the use of Zaharov equation, and the results compare extremely well with experimental data. Moreover the Zaharov equation was used to investigate wave dynamics as a function of the bandwidth of components in a spectrum as well as of the wave steepness. The dispersion of the components of a wave train lies between that of a highly dispersive linear system and an effectively non-dispersive phase locked system (in which component travel at essentially a single speed), depending on the bandwidth and steepness of the group (Fig. 7.4).

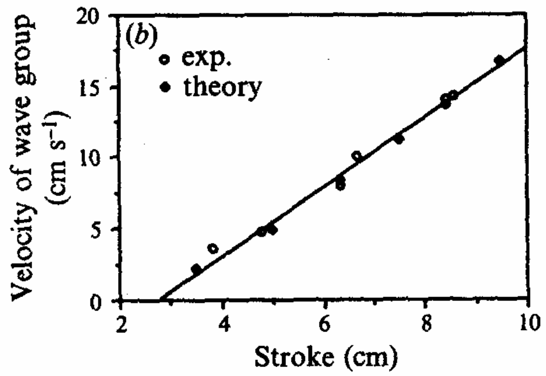


Figure 7.2 Non-linear sloshing wave group speed in a channel as a function of wavemaker stroke near tank resonance (Yao et al., 1994).

Longuet-Higgins & Dommermuth (1997) studied the crest instabilities of waves by a boundary-integral time-stepping method, applying a perturbation to an almost highest wave.

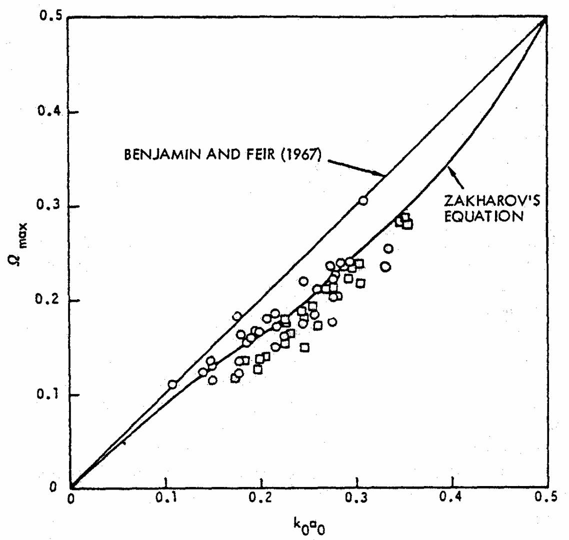


Figure 7.3 Most unstable modulation frequency Ω_{MAX} as a function of carrier wave steepness k_0a_0 (Yuen & Lake, 1980).

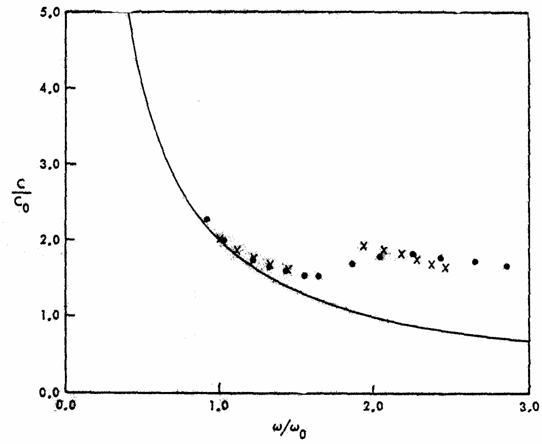


Figure 7.4 Normalized component phase speed $C/C_0 Vs$ normalized frequency ω/ω_0 (× numerical computation, • experimental data, —— linear dispersion) (Yuen & Lake, 1980).

They found that the development of instability depends crucially on the sign of the initial perturbation, a positive perturbation leading to overturning, a negative perturbation leading to a transition of the wave to an almost steady wave of lower amplitude. Their results do not take into account surface tension or viscosity. See also Wang et al. (1995) referred in section 7.2.

Spatial variations. Chaplin (1996) and Contento et al. (2001) have shown by experiments and by fully non-linear numerical simulations respectively that frequency-focused waves behave in a strongly non-linear manner in the region around the focus point. Results are shown in Fig. 7.5. In both cases maximum wave elevations exceeded linear predictions locally by more than 15%, due to the presence of self-induced components at frequencies well above the input spectrum.

Non-linear wave-wave interactions lead to phase shifts at the focus point and at the same time these new high frequency components have an almost constant phase speed. Both simulations and experiments refer to a closed wave flume. Even though the experiments and the simulations were for slightly different input spectra at the wavemaker, the comparison is surprisingly good (Figure 7.5).

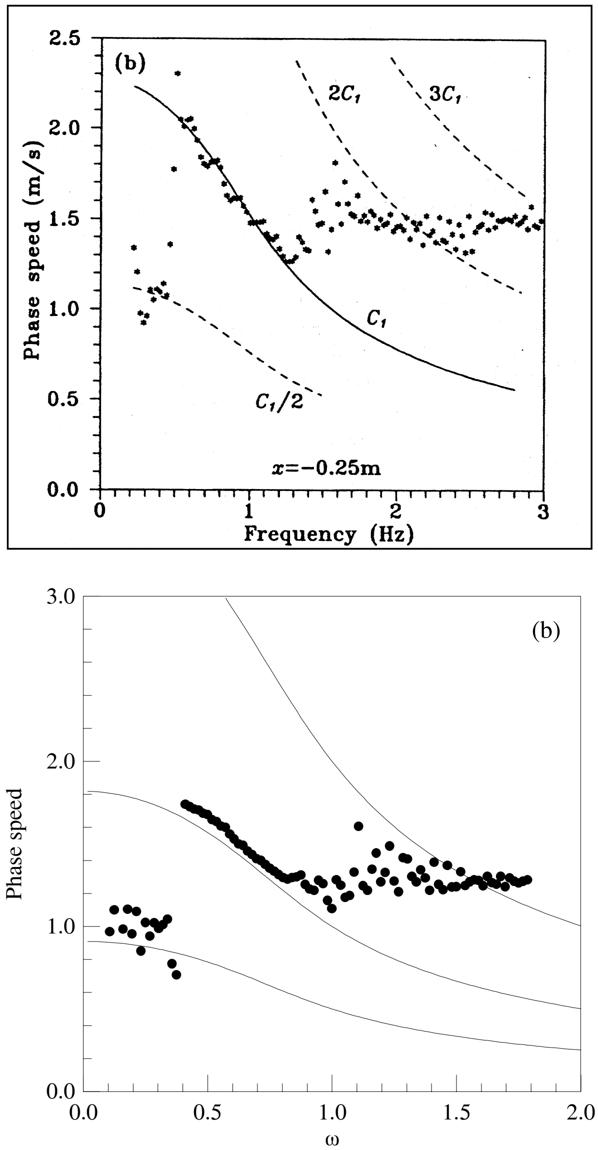


Figure 7.5 Component phase speeds as functions of wave frequency near the focus point. Above: experimental results from Chaplin (1996); below: numerical results from Contento et al. (2001).

Reflection effects. Cotter & Chakrabarti (1992) discuss 3 methods of computing wave reflection coefficients in a basin with regular assumed sinusoidal waves. These are based on 2 fixed probes, 3 fixed probes measuring the elevation and phase lag, and 3 probes measuring the wave height only. They show that the assumed wave length plays a fundamental role in the accuracy of the results, and that those derived from linear theory are quite unreliable. They suggest that the wave length should be derived from $L=Td/t$, where T is the wave period, d the distance between two probes, and T the time elapsed between two maxima in the water surface elevation. The best results in terms of stability and accuracy are those derived with two probes (see Figure 7.6), assuming a wave length derived in this way. It is shown that a 2.8% error in the wavelength takes the computed reflection coefficient from 5% to 20%. Any non-linearity is not taken into account.

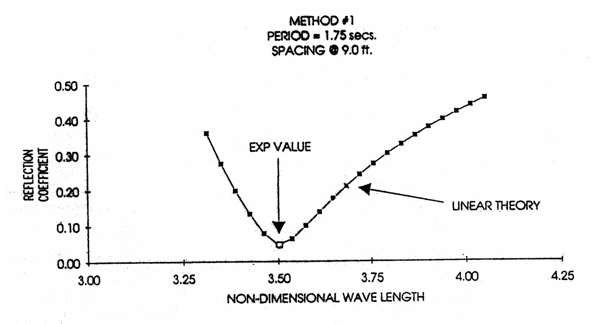


Figure 7.6 Effect of the choice of the wave number on the reflection coefficient (Cotter and Chakrabarti, 1992).

Zhu (1999) has presented a TFM method which can separate a regular wave field into incident and reflected waves based on linear wave theory. The method is compared with 3 others taken from the literature and is found to provide estimates of incident and reflected wave heights at least one order more accurate than the others. This is explained by the fact that the method does not rely on a calculation of phase differences between wave signals recorded by neighbouring wave gauges.

7.2. Numerical methods for time dependent free surface flows

In this section, the main numerical methods to deal with explicitly unsteady non-linear free-surface flows are briefly described. They can be roughly divided between:

- Boundary-discretization, or boundary element, methods (BEM), relying on an

integral formulation of the boundary value problem are used for potential flows.
- Volume-discretization methods, in principle applicable to both viscous and inviscid problems, based on the point-wise application of the field equations.

Boundary discretization methods. The numerical scheme can roughly be described by the two-step procedure:
1. at each time step the velocity field has to be evaluated from the boundary conditions;
2. the free-surface boundary conditions and equations of body motion are integrated in time to update the geometry of the boundary and the relevant boundary data.

In this framework large-scale computations are made feasible both by increasing the accuracy of the boundary-integral equation solver and by accelerating the solution of the integral equations. The first point is accomplished either by adopting high-order boundary-element methods, or by using desingularized methods. The second issue can be accomplished by each of the following techniques: domain-subdivision techniques, clustering techniques, precorrected-FFT methods and multipole expansion with fast summation coupled to iterative solvers (Kormeyer et al., 1993; Scorpio et al., 1996; Graziani & Landrini, 1998).

Apart from fundamental studies concerning wave dynamics, the main goal of the above approaches is the global prediction of the inviscid part of the wave-induced forces. More detailed studies focus on detecting breaking events and predicting the occurrence of water on deck. For seakeeping studies, the solution can be coupled with the equations of motion of a vessel to provide predictions of non-linear ship dynamics.

Boundary-integral approaches can follow wave breaking up to the formation of jets or plunging breakers. But post-breaking behaviour still lacks theoretical and numerical description (Soding, 1977).

Wang et al. (1995) presented an efficient numerical tank for non-linear water waves, based on a multi-subdomain approach with BEM. The aim of the work was to obtain long simulations in a long tank ($O(10^2)$ wavelengths) with acceptable computing times. The method splits the long wave tank into a number of sections with appropriate boundary conditions at the interfaces. The number of unknowns is thus increased, but the resulting linear system has favourable properties for an efficient numerical solution. Wang et al. applied this approach to a study of the stability of regular waves subjected to side-band disturbances. They also describe a method for suppressing local breaking that is claimed to prevent the break-down of the simulation without affecting the accuracy of global solution.

Tulin et al. (1994) simulated the evolution, deformation and breaking of wave groups in a long wave tank by a multi-subdomain approach. Their method allows the vorticity created during breaking to be quantified.

Graziani & Landrini (1998) presented an application of a multipole expansion technique to two-dimensional non-linear free surface flows. The integral representation of the velocity field allows for the iterative solution of the related integral equations. A remarkable reduction of the computational effort is achieved by coupling to the iterative solver a fast summation technique based on the multipoles expansion of the influence coefficients.

Landrini et al. (1999) proposed a two-dimensional B-Spline based method for unsteady free surface flows. The method shows extreme robustness against violent displacements of rigid walls.

On the suppression of wave breaking in long time simulations, Subramani & Beck (2000) presented a numerical scheme to prevent the premature break-down of non-linear BEM simulations including the case of forward speed. This regards bow and transom-stern breaking.

Wu et al. (2000) presented a numerical procedure for the reconstruction of irregular non-linear wave-fields using wave records of limited duration at one or more fixed points. Their aim was to obtain the complete kinematics of entire non-linear wave-field including forecasts of non-linear wave-field evolution dynamics beyond the scope of the input data. The procedure is based on a three level optimization scheme:

(1) a linear wave solution with a given number of free modes is fitted to the record;
(2) a second order Stokes solution is fitted to the record starting from the linear one;
(3) finally a higher order spectral method is used iteratively (starting from the results of level (2) until experimental and numerical data differ by a specified threshold in the time domain).

Their procedure has been applied to wave data from Stansberg et al. (1995) showing extremely good convergence even in the presence of large episodic waves.

Using numerical simulations Saffman & Yuen (1979) discussed the existence of large amplitude standing waves with steepness greater that 0.218 and maximum slopes exceeding 45°.

Volume Discretization Methods. Beside the need to solve viscous flows at high Reynolds numbers in the field of ship hydrodynamics, volume discretization methods are of interest because they are apparently more robust than boundary discretizations in dealing with breaking flows. A number of methods have been formulated to try to capture wave making with various degrees of success. These include the following groups:

(1) Boundary fitted methods, or interface tracking methods, which define the free surface as a sharp interface. The physical domain is then mapped into a more regular computational domain on which the problem is solved via finite differences, or finite volume techniques. Problems may be encountered when the free surface starts folding or when the grid has to be moved along walls of a complicated shape. Unstructured and multi-block grids can deal with complex geometries and large free surface deformations.
(2) Eulerian-grid methods, or interface capturing methods (Muzaferija et al., 1997, 1998), in which the computation is performed on a fixed (usually rectangular) grid which extends also over the air region. The free surface is not defined as a sharp interface and its shape is determined by finding the cells which are only partly filled with fluid. Schemes include marker-and-cell (MAC), volume of fluid (VOF), and level set techniques. Among examples are Miyata et al. (1987, 1992) who developed and applied a finite volume method for the simulation of the viscous flow around an advancing ship. Park & Miyata (1994) applied a finite difference method to the study of 2D and 3D breaking waves. Lin & Liu (1998) studied by a volume of fluid method the breaking of waves in the surf zone. In the case of a spilling breaker, the wave elevation at different locations given by the proposed model compared very well with laboratory data, mostly in the inner surf zone. They also derived qualitative and quantitative features of the spilling breaking process, including particle velocities and vorticities, and pressure distributions.
(3) Gridless methods. In principle, problems of adapting the grid to large deformations of the fluid domain can be avoided by removing the grid. The field equations are discretised by using points irregularly scattered over the computational domain. In some cases, the computational points have a physical meaning and represent fluid particles. In this case a Lagrangian method is obtained and was first intro-

duced by Monhagan (1992), called Smooth Particle Hydrodynamics (SPH). The key concept is the possibility of representing fluid quantities in terms of interpolating operators based on scattered data. Belytschko et al. (1996) presented an overview on meshless methods. An application of SPH method to breaking waves was presented by Landrini et al. (2001).

8. COASTAL ENGINEERING PRACTICE AND COMPATIBILITY WITH ITTC

8.1. Introduction

There are well-established procedures in the coastal engineering community for the simulation of nearshore waves. These include procedures used for the physical modeling of waves in shallow water coastal engineering wave basins, and for numerical modeling of waves over the nearshore bathymetry. This is complemented by an extensive body of knowledge of the behavior of shallow water waves based on mathematical theories and field observations.

The simulation of waves in finite depth may be of interest to ITTC members because of the increased emphasis placed on ship operations in near shore and coastal waters. Many navies of the world have an emphasis on operating in the 'littoral zone' where waves interact with the sea floor. Commercial ship operators likewise have a greater interest in coastal operations, owing to the economic pressures to move ships in and out of port through navigation channels where the ship draft may be nearly the same as the water depth. Similar interests in nearshore waves arise any time ships are moored inside the confines of a harbor.

Wave height and propagation directions can be strongly modified by the processes of shoaling, refraction, and diffraction as waves move into finite depth or over uneven bathymetry. These processes can lead to either growth or reduction of wave height depending on the site-specific conditions. Regardless of these changes in wave height, the reduced wavelength leads to a large increase in wave steepness as waves enter shallower water depths. As a result, ship motions that are sensitive to wave steepness or wave slope, such as pitch and roll, can be quite different in shallow water compared to deep water.

In addition to these modifications, individual wave forms become more asymmetric and non-linear in finite depth when compared to deep water wave forms. Surface elevations for individual waves of appreciable height in finite depth are not sinusoidal, and the statistics of the sea surface in a random sea may become strongly non-Gaussian. Wave height statistics in finite depth may depart from the traditional Rayleigh distribution used in deep water. Wave crest amplitudes in shallow water waves are substantially larger than trough amplitudes due to enhanced non-linearities. All of these factors may cause shallow water ship operations to differ from deep water.

8.2. Fundamental Properties of Waves in Finite Depth

Waves in finite depth are characterized in the coastal engineering literature in much the same way that deep-water waves are characterized in the naval architecture literature, through a combination of deterministic and non-deterministic parameters.

In this section, we first review basic deterministic properties of individual waves in finite depth. A subsequent section deals with the non-deterministic properties of irregular sea states in finite depth. The emphasis is to point out areas where differences exist between coastal engineering practice and traditional naval architecture practice in deep water.

8.2.1. Basic wave properties – Wavelength and Celerity

The fundamental wave properties of wave length and wave celerity in finite depth are commonly simulated using the linear or 1st order wave theory. It is widely recognized in coastal engineering that the validity of the linear theory becomes increasingly questionable as the relative depth h/L_o decreases and as the wave steepness, H_w/L_w, increases. However, the linear theory still forms the basis for most descriptions of waves in finite depth, particularly for spectral descriptions of random seas.

The linear theory defines individual wave forms that are sinusoidal with a well defined wave period, T_w, wave height, H_w, and crest-trough symmetry so that both crest and trough amplitudes equal $H_w/2$. In deep water, the theory provides well-known expressions relating wavelength and wave celerity to wave period. In coastal engineering practice, it is common to add a subscript 'o' to denote 'deep water'. As a result, the familiar expressions for deep water wave length and celerity are given by $L_{wo} = gT_w^2/2\pi$ and $C_{wo}=gT_w/2\pi$.

As waves move into finite depth, the wave period remains constant. The wave length and wave speed are, however, reduced from their deep water values as

$$\begin{aligned} L_w &= \frac{gT_w^2}{2\pi}\tanh\left(\frac{2\pi h}{L_w}\right) \\ &= L_{wo}\tanh\left(\frac{2\pi h}{L_w}\right) \end{aligned} \tag{5}$$

and

$$\begin{aligned} C_w &= \frac{gT_w}{2\pi}\tanh\left(\frac{2\pi h}{L_w}\right) \\ &= C_{wo}\tanh\left(\frac{2\pi h}{L_w}\right) \end{aligned} \tag{6}$$

Waves may be classified as either being in 'deep water' or 'finite depth' depending on the behavior of the hyperbolic tangent function in Equation (5). Deep water waves correspond to conditions where $h/L_w > 0.5$ as this gives $\tanh(2\pi h/L_w)\sim 1$. For this condition, $L_w=L_{wo}$. Waves are considered to be in 'finite depth' or 'transitional depth' when $h < 0.5L_w$.

In coastal engineering practice, waves are considered to be in 'shallow water' when $h/L_w<0.05$, or equivalently when $h/L_{wo}<0.0155$. Under these conditions, $\tanh(2\pi h/L_w)\sim 2\pi h/L_w$, and Equations (5) and (6) can be greatly simplified to give $L_w=T_w(gh)^{1/2}$ and $C_w = (gh)^{1/2}$. These 'shallow water' equations describe the length and speed of very low frequency long waves that often excite large motions of moored vessels in harbors.

The wave steepness, H_w/L_w, can be greatly increased in finite depth. Irrespective of any changes in wave height that may occur in finite depth, the reduction in wave length generally leads to increased values of wave steepness as the depth is reduced. Ship motions that depend on wave steepness may therefore be quite different in finite depth compared to deep water.

Finally, Equation (6) indicates that wave speed C_w decreases in finite depth. This is also evident from the basic relationship for periodic waves where $C_w=L_w/T_w$. This may be important with regard to ship motions that depend on the encounter period between the moving ship and waves. In head seas, for example, the encounter period is given by $T_e=T_w/(1+V_s/C_w)$ and will be smaller in finite depth than in deep water.

8.3. Non-Linear Effects

Linear wave theory is commonly used in coastal engineering to provide a general description of regular wave properties spanning the range from deep to shallow water across the full range of finite water depths. It is well known, however, that waves are inherently non-linear in finite depth, particularly the largest waves which occur during design conditions when the wave steepness, H_w/L_w, is high.

Several characteristics of non-linear waves may be of importance for ship operations in finite depth. Most fundamentally, non-linear waves are non-sinusoidal with crest amplitudes that exceed $0.5H_w$ and trough amplitudes that are less than $0.5H_w$. This asymmetry is present in very steep waves in deep water, but it is magnified as waves enter finite depth. By the time waves break at the outer edge of the surf zone in shallow water, crest amplitudes may be on the order of $0.7H_w$ to $0.9H_w$ while trough amplitudes are only $0.1H_w$ to $0.3H_w$. In intermediate depths, where ship operations may be expected, crest amplitudes may be $0.6H_w$ to $0.7H_w$. Such asymmetry may affect seakeeping and deck wetness in finite depths.

Non-linear waves also exhibit some changes in wave length, wave celerity, and wave height that differ from linear waves. Non-linear wave theories suggest that wave length and celerity both increase weakly with increasing wave steepness and decreasing water depth. This effect is often ignored but can give wavelengths that are more than 10% larger than would be computed using linear theory. Wave shoaling processes also are enhanced for non-linear waves when compared to linear waves. As a result, non-linear waves will shoal to a higher height and break somewhat farther seaward than would be suggested by linear theory. Goda (2000) and others illustrate this effect.

The fluid orbital motions of non-linear waves also differ from those of linear waves. While linear waves have closed elliptic orbits in finite depth, non-linear waves have orbital motions that are not closed. These are asymmetric with larger forward motions under the wave crests which are not fully compensated by the weaker motions under the wave trough. As a result, non-linear waves produce a net shoreward mass transport or drift current that can move a stationary ship slowly toward shore (along with wave drift forces)

Several theories are available for predicting specific properties of non-linear waves. Most theories are two-dimensional and assume no refraction or diffraction effects. The applicability of these non-linear theories can be discussed in regard to the Ursell Parameter, $U_r = H_w L_w^2/h^3$.

In deep water, and in finite depth where the $U_r < 26$, the Stokes 2nd-order, 3rd-order, and 5th-order wave theories can be used. These theories all become invalid in shallow water but can be used in many finite depth conditions. These theories all model the fundamental effects of non-linearity. For example, as steepness increases, the Stokes 3rd and 5th order theories suggest that both wavelength and celerity increase slightly (a few percent) over the value computed using linear theory. The wave form changes more significantly however, as the Stokes theories yield an asymmetric wave profile with elevated wave crests and truncated wave troughs.

8.4. Irregular Waves in Finite Depth

The simulation of irregular waves in finite depth follows the same general procedures used in deep water, as waves may be characterized by: (1) their bulk parameters of significant wave height and peak spectral wave period, (2) their spectrum, and/or (3) their probability distributions.

Most spectral formulations for waves in finite depth are linear in that they represent the sea through summations of many linear sinusoidal wave components. Recent research in coastal engineering has considered the effects of non-linear wave-wave interactions in nearshore wave spectra. But at present, these are not fully incorporated into standard design practice.

As a result, the effects of non-linearity in irregular wave in finite depths is most frequently incorporated through use of empirical descriptions of the basic statistical and probabilistic properties of nearshore sea states.

9. CONCLUSIONS AND RECOMMENDATIONS

9.1. Spectral formulation and documentation

A variety of spectral formulations are in use for short-term spectrum modeling. However, many of them are different forms of each other, or closely related. Basically, the formulations used for laboratory modelling of point (omni-directional) spectra can be reduced into three types:

- Bretschneider, or 2-parameter Pierson-Moskowitz (B/PM)
- JONSWAP (of which B/PM is one special type
- Ochi-Hubble

or composed from these. In addition, there exist more general forms taking into account finite depths and other limited conditions. Two-peaked spectra (swell + wind sea) are becoming increasingly important for the analysis of marine structures, with point spectra modeled either as a combination of JONSWAP peaks, or by the Ochi-Hubble formulations. The detailed shape of swell components is still a matter of discussion, and progress will rely on further analysis of field data.

Waves are most often modeled either as uni-directional, or with uni-directional wind sea and swell components in different directions. Directional spreading is more and more frequently being included. The significance of the spreading for vessel responses has been documented, but could be even better clarified. It is likely to become more widely used in testing as more directional field data is accumulated and interpreted. A frequency-dependent directional spreading formulation of the $\cos^n(\theta/2)$-type or similar is most often used to model the directional spreading of energy about each spectral peak.

Model test facilities seek to reproduce whatever wave spectrum is specified without necessarily preferring one model formulation over the other. However the proper documentation of spectra generated in model tests is essential. This should include the method of analysis, as well as a comparison of the measured and the target spectra. For directional spectra, it is particularly important to record both the actual measurement locations (the wave gage array) and the method of analysis, since the results are sensitive to both.

The 23rd ITTC Waves Committee concludes that at present, spectral models used for model tests should be based on the most common formulations available today, with no particular model preferred. This includes single-peaked as well as two-peaked spectra, for unidirectional and directional spread sea. However, a better standardization of the parameters used is recommended, since several of the existing formulations are closely related or even expressions of the same model.

9.2. Non-linear phenomena and extreme waves

Non-linear effects are observed in laboratory random wave modeling as well as in field data, and in most cases they compare roughly with second-order predictions. Resulting effects may be essential for various vessel loads and responses, and should be properly documented when they are expected to be relevant, especially in steep sea states and in finite and shallow water. Methods and parameters for relevant characterization have been suggested in the literature.

Modeling of extreme waves, their analysis and documentation, requires special attention. The probability of occurrence, corresponding stochastic variability, possible effects from higher-order contributions and breaking, are matters of continuous research and development. They may be modeled either by deterministic methods (transient waves), or by stochastic representations. Comparison with available theoretical or numerical models adds value to model tests.

9.3. Waves on currents and in finite water

The generation of waves on currents and in finite and shallow water depths introduces additional challenges in model testing. A collinear current introduces a wave height reduction, while an opposing current does the opposite, but in calibration this is normally adjusted with the current turned on. Non-linear wave-current interactions also occur, with the waves affecting the current and vice versa. The current also affects resulting wave loads. In addition, current generation over an area normally introduces inhomogeneities in the wave field, giving rise to refraction effects. This often limits the area of useful wave generation with current, and should be documented when relevant.

Wave generation in finite and shallow water is subject to stronger non-linearities, and dissipation by breaking at an earlier threshold. As a result, wave spectra change in space. Wave generation is also subject to stronger influences of so-called parasitic free waves from the wave paddle. With the bottom not perfectly horizontal, refraction effects will occur. Finally, vessel loads and responses may be different from deepwater conditions, e.g. because particle orbits are elliptical and not circular, and because non-linearities associated with finite depth such as enhanced wave asymmetry are generated.

9.4. Reflections and other unwanted effects

Over recent years, various methods have been developed to enable the effects of reflections from the beach and walls, and diffraction, to be avoided or reduced. In general, it is recommended that these features should at least be investigated and mapped in existing facilities. The most sophisticated technique for mitigating these unwanted effects is active absorption. This has a great potential, but it is still a complex and demanding tool for routine use in existing laboratories, and is still under development for directional waves. When fully exploited, it will allow useful areas in directional wave basins to be significantly increased.

Spatial variations and wave train instabilities may be introduced not only by reflections and diffraction, but also by physical mechanisms in the waves themselves (as in the real sea). The importance of documenting the wave field over the area used in tests is emphasized.

Laboratory wave generation also introduces non-linear unwanted effects (‘parasitic waves’), for which various numerical analysis procedures have been published. These effects are most significant in finite and shallow water. The implementation for practical application in laboratories is still at an early stage.

9.5. Numerical modelling and interaction with model tests

The integration of numerical models with tank testing adds great value to the interpretation of the tests. This may include models ranging from linear to fully non-linear, such as numerical wave tanks (NWT) and CFD. The combined use of numerical and physical models helps in the understanding of observed phenomena, and also in the interpretation of unwanted effects such as reflections and parasitic waves. In addition, planning of the experiments can be improved. It is expected that this integrated approach will further mature in the future.

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APPENDIX A. SPECTRAL FORMULATIONS

This appendix presents some commonly used point (omni-directional) wave spectra in a consistent format. The spectra are given either in the form $S(f)$ (with dimensions m^2/Hz) or $S(\omega)$ (m^2/rads/s) according to their derivation or common usage in each case. If $\omega = 2\pi f$, then $S(f) = 2\pi S(\omega)$.

All expressions are valid in any consistent system of units, except where stated otherwise.

Table A.1 Definitions.

Symbol	S.I. Units	Definition
g	ms^{-2}	gravitational acceleration
H_s	m	significant wave height; $H_s = 4\sigma_\eta$ assuming the spectrum is narrow-banded.
m_n	$m^2\,(Hz)^n$ or $m^2(rads/s)^n$	n-th spectral moment; $m_n = \int_0^\infty S(f) f^n\, df$ or $m_n = \int_0^\infty S(\omega)\omega^n\, d\omega$, depending on the context
$\boldsymbol{U}$	ms^{-1}	windspeed
$\boldsymbol{F}$	m	fetch
σ_η	m	standard deviation of the water surface elevation; $\sigma_\eta^2 = \int_0^\infty S(f)df = \int_0^\infty S(\omega)d\omega$
f_E , ω_E	Hz, rads/s	energy frequency; $f_E = 1/T_E = m_0/m_{-1}$, or $\omega_E = m_0/m_{-1}$, depending on the context
$\overline{f}$, $\overline{\omega}$	Hz, rads/s	mean frequency; $\overline{f} = 1/\overline{T} = m_1/m_0$, or $\overline{\omega} = m_1/m_0$
f_z , ω_z	Hz, rads/s	zero-crossing frequency; $f_z = 1/T_z = \sqrt{m_2/m_0}$, or $\omega_z = \sqrt{m_2/m_0}$
f_p , ω_p	Hz, rads/s	spectral peak or modal frequency
f_n , ω_n	Hz, rads/s	frequency corresponding to the n% energy threshold, $\frac{\int_0^{f_n} S(f)df}{\int_0^\infty S(f)df} = \frac{\int_0^{\omega_n} S(\omega)d\omega}{\int_0^\infty S(\omega)d\omega} = \frac{n}{100}$; 98% of the energy is within the range $\omega_1 < \omega < \omega_{99}$

Table A.2 Generalised Pierson Moskowitz or Bretschneider spectrum.

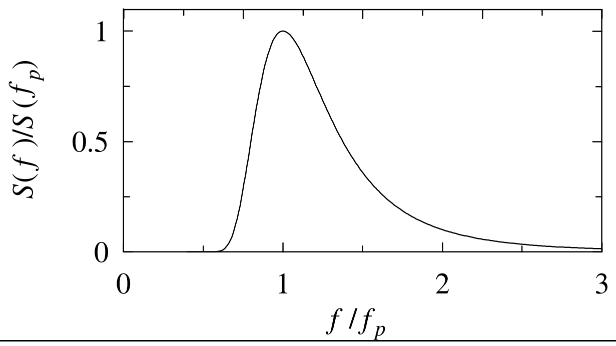
Spectral form	$S(f)=\frac{A}{f^5}\exp(-B/f^4)$
Significant wave height	$H_s=2\sqrt{A/B}$
Energy frequency	$f_E = m_0/m_{-1} = \frac{2\sqrt{2}\Gamma(3/4)B^{1/4}}{\pi} = 1.103B^{1/4}$
Mean frequency	$\bar{f} = m_1/m_0 = \Gamma(3/4)B^{1/4} = 1.225B^{1/4} = 1.111 f_E$
Zero-crossing frequency	$f_z = \sqrt{m_2/m_0} = (\pi B)^{1/4} = 1.331B^{1/4} = 1.087\bar{f} = 1.207 f_E$
Spectral peak frequency	$f_p = (4B/5)^{1/4} = 0.946B^{1/4} = 0.711 f_z = 0.772\bar{f} = 0.858 f_E$
m_{-1}	$m_{-1} = \frac{\sqrt{2}\pi A}{16\ \Gamma(3/4)\, B^{5/4}} = 0.2266\frac{A}{B^{5/4}}$
m_0	$m_0 = \sigma_\eta^2 = \frac{A}{4B}$
m_1	$m_1 = \Gamma(3/4)\frac{A}{4B^{3/4}} = 0.306\frac{A}{B^{3/4}}$
m_2	$m_2 = \frac{A}{4}\sqrt{\frac{\pi}{B}} = 0.443\frac{A}{\sqrt{B}}$
m_3	$m_3 = \frac{A\pi}{2\sqrt{2}\ \Gamma(3/4)B^{1/4}} = 0.906\frac{A}{B^{1/4}}$
Energy thresholds	$f_{0.1} = 0.652 f_p$; $f_1 = 0.722 f_p$; $f_{50} = 1.159 f_p$; $f_{99} = 3.340 f_p$; $f_{99.9} = 5.946 f_p$
Spectral plot	
Key reference	Bretschneider (1959)

Table A.3 Spectra of the generalised Pierson Moskowitz form.

Pierson-Moskowitz spectrum	
Input parameter	U (at 19.5m) or f_p or H_s
A and B in Table 1	$A = \alpha g^2 (2\pi)^{-4}$, $B = \beta(2\pi U/g)^{-4}$ or $B = (5/4) f_p^4$ or $B = 4\alpha g^2/[(2\pi)^4 H_s^2]$ $\alpha = 0.0081$, $\beta = 0.74$
Key reference	Pierson & Moskowitz (1964)
Two-parameter Pierson-Moskowitz spectrum	
Input parameters	f_p and H_s
A and B in Table 1	$A = \frac{5H_s^2 f_p^4}{16}$, $B = \frac{5 f_p^4}{4}$
ISSC spectrum	
Input parameters	H_s and $\overline{f}$
A and B in Table 1	$A = 0.1107 H_s^2 \overline{f}^4$, $B = 0.4427 \overline{f}^4$
Key reference	ISSC (1964)
ITTC spectrum	
Input parameters	H_s and one of the following: T_E, T_p, $\overline{T}$, T_z
A and B in Table 1	$A = \frac{0.0081}{K^4} g^2$, $B = \frac{0.0081}{K^4} \frac{4g^2}{H_s^2}$ $K = \frac{T_E}{2.137}\sqrt{\frac{g}{H_s}}$, $K = \frac{T_p}{2.492}\sqrt{\frac{g}{H_s}}$, $K = \frac{\overline{T}}{1.924}\sqrt{\frac{g}{H_s}}$, or $K = \frac{T_z}{1.771}\sqrt{\frac{g}{H_s}}$.
Key references	ITTC (1969), Matthews (1972)
Liu spectrum	
Input parameters	U and F
A and B in Table 1	$A = \alpha g^2 \hat{F}^{-1/4} (2\pi)^{-4}$; $B = \beta\, (2\pi U_*/g)^{-4}\, \hat{F}^{-4/3}$; $\alpha = 0.4$, $\beta = 0.0055$, $\hat{F} = gF/U_*^2$; $U_* = U/(U^2/gF)^{1/3}$
Key reference	Liu (1971)

Table A.4 JONSWAP spectrum.

Seas with finite fetch. Approximations (using default values for τ) are believed to be correct to within 0.5% over the range $1 < \gamma < 7$. U is the windspeed at an elevation of 10 m.

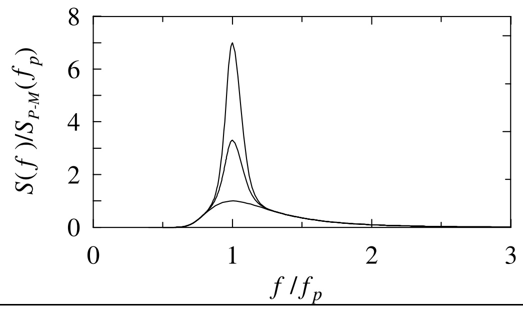
Input parameters	f_p and γ. When U and F are known, $f_p = (g/U)\hat{F}^{-1/3}$, where $\hat{F} = gF/U^2$
Spectral form	$S(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp\left[-\frac{5}{4}\left(\frac{f}{f_p}\right)^{-4}\right] \gamma^{\exp\left[-\frac{(f-f_p)^2}{2\tau^2 f_p^2}\right]}$
Default values for τ and α	$\tau = 0.07, f \le f_p$, $\tau = 0.09, f > f_p$. $\alpha = 0.0081$, or $\alpha = 0.076\,\hat{F}^{-0.22}$
Approximate spectral form	$S(f) = 2\pi\alpha^* H_s^2 \frac{f^{-5}}{f_p^{-4}} \exp\left[-\frac{5}{4}\left(\frac{f}{f_p}\right)^{-4}\right] \gamma^{\exp\left[-\frac{(f-f_p)^2}{2\tau^2 f_p^2}\right]}$ $\alpha^* = \frac{0.0624}{0.230 + 0.0336\gamma - 0.185(1.9+\gamma)^{-1}}$
Energy frequency	$f_E = f_p / (0.8255 + 0.03852\gamma - 0.005537\gamma^2 + 0.0003154\gamma^3)$
Mean frequency	$\bar{f} = f_p / (0.7303 + 0.04936\gamma - 0.006556\gamma^2 + 0.0003610\gamma^3)$
Zero-crossing frequency	$f_z = f_p / (0.6673 + 0.05037\gamma - 0.006230\gamma^2 + 0.0003341\gamma^3)$
Significant wave height	$H_s = (1.555 + 0.2596\gamma - 0.02231\gamma^2 + 0.001142\gamma^3) g\sqrt{\alpha}/(2\pi f_p)^2$
m_{-1}	$m_{-1} = (0.1195 + 0.05561\gamma - 0.003033\gamma^2 + 0.0001595\gamma^3) g^2\alpha/(2\pi f_p)^5$
m_0	$m_0 = (0.1475 + 0.05617\gamma - 0.003077\gamma^2 + 0.0001618\gamma^3) g^2\alpha/(2\pi f_p)^4$
m_1	$m_1 = (0.2059 + 0.05705\gamma - 0.003154\gamma^2 + 0.0001661\gamma^3) g^2\alpha/(2\pi f_p)^3$
m_2	$m_2 = (0.3420 + 0.05827\gamma - 0.003269\gamma^2 + 0.0001723\gamma^3) g^2\alpha/(2\pi f_p)^2$
m_3	$m_3 = (0.8015 + 0.05984\gamma - 0.003422\gamma^2 + 0.0001807\gamma^3) g^2\alpha/(2\pi f_p)$
Energy thresholds	$f_{0.1} = (0.6477 + 0.005357\gamma - 0.0002625\gamma^2) f_p$ $f_{99.9} = (6.3204 - 0.4377\gamma + 0.05261\gamma^2 - 0.002839\gamma^3) f_p$
Spectral plots for γ = 1, 3.3, 7	
Key references	Hasselman et al. (1973), Ewing (1975), Goda (1979)

Table A.5 Scott spectrum.

Fully developed seas. The parameters of the Scott spectrum are not dimensionless.

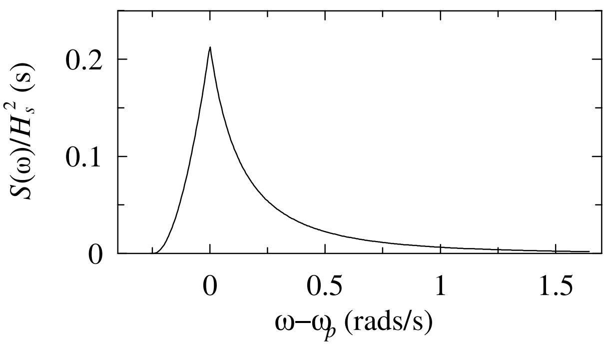
Input parameters	H_s and ω_p
Spectral form	$S(\omega)=0$, for $(\omega-\omega_p)<0.26$, $S(\omega)=0.214H_s^2\ exp\left[-\sqrt{\dfrac{(\omega-\omega_p)^2}{0.065\ (\omega-\omega_p+0.26)}}\right]$, for $-0.26<(\omega-\omega_p)<1.65$, $S(\omega)=0$, for $1.65<(\omega-\omega_p)$.
m_0	$m_0=\sigma_\eta^2=0.063H_s^2$
m_1	$m_1=(0.0120+0.063\omega_p)H_s^2$
m_2	$m_2=(0.0087+0.0240\omega_p+0.188\omega_p^2)H_s^2$
m_3	$m_3=(0.0080+0.0262\omega_p+0.108\omega_p^2+0.817\omega_p^3)H_s^2$
Spectral plot	
Key reference	Scott (1965)

Table A.6 Ochi-Hubble bi-modal spectrum.

Finite fetch and duration. There is just one input parameter, but the spectrum has 11 forms, comprising the most probable form, and 10 others that characterise the measured data to within the 95% confidence limits.

Input parameters	H_s
Spectral form	$S(\omega) = \frac{1}{4} \sum_{j=1,2} \frac{\left(\frac{4\lambda_j + 1}{4} \omega_{pj}^4 \right)^{\lambda_j}}{\Gamma(\lambda_j)} \frac{H_{sj}}{\omega^{4\lambda_j + 1}} exp\left[- \frac{4\lambda_j + 1}{4} \left(\frac{\omega_{pj}}{\omega} \right)^4 \right]$
Key reference	Ochi & Hubble (1976)

Most probable spectrum (H_s in metres):					
H_{s_1}	H_{s_2}	ω_{p_1}	ω_{p_2}	λ_1	λ_2
$0.84H_s$	$0.54H_s$	$0.70\exp(-0.046H_s)$	$1.15\exp(-0.039H_s)$	3.00	$1.54\exp(-0.062H_s)$

Spectra within 95% confidence limits (H_s in metres):					
H_{s_1}	H_{s_2}	ω_{p_1}	ω_{p_2}	λ_1	λ_2
$0.95H_s$	$0.31H_s$	$0.70\exp(-0.046H_s)$	$1.50\exp(-0.046H_s)$	1.35	$2.48\exp(-0.102H_s)$
$0.65H_s$	$0.76H_s$	$0.61\exp(-0.039H_s)$	$0.94\exp(-0.036H_s)$	4.95	$2.48\exp(-0.102H_s)$
$0.84H_s$	$0.54H_s$	$0.93\exp(-0.056H_s)$	$1.50\exp(-0.046H_s)$	3.00	$2.77\exp(-0.112H_s)$
$0.84H_s$	$0.54H_s$	$0.41\exp(-0.056H_s)$	$0.88\exp(-0.026H_s)$	2.55	$1.82\exp(-0.089H_s)$
$0.90H_s$	$0.44H_s$	$0.81\exp(-0.052H_s)$	$1.60\exp(-0.033H_s)$	1.80	$2.95\exp(-0.105H_s)$
$0.77H_s$	$0.64H_s$	$0.54\exp(-0.039H_s)$	0.61	4.50	$1.95\exp(-0.082H_s)$
$0.73H_s$	$0.68H_s$	$0.70\exp(-0.046H_s)$	$0.99\exp(-0.039H_s)$	6.40	$1.78\exp(-0.069H_s)$
$0.92H_s$	$0.39H_s$	$0.70\exp(-0.046H_s)$	$1.37\exp(-0.039H_s)$	0.70	$1.78\exp(-0.069H_s)$
$0.84H_s$	$0.54H_s$	$0.74\exp(-0.052H_s)$	$1.30\exp(-0.039H_s)$	2.65	$3.90\exp(-0.085H_s)$
$0.84H_s$	$0.54H_s$	$0.62\exp(-0.039H_s)$	$1.03\exp(-0.030H_s)$	2.60	$0.53\exp(-0.069H_s)$

Plots for H_s = 10m

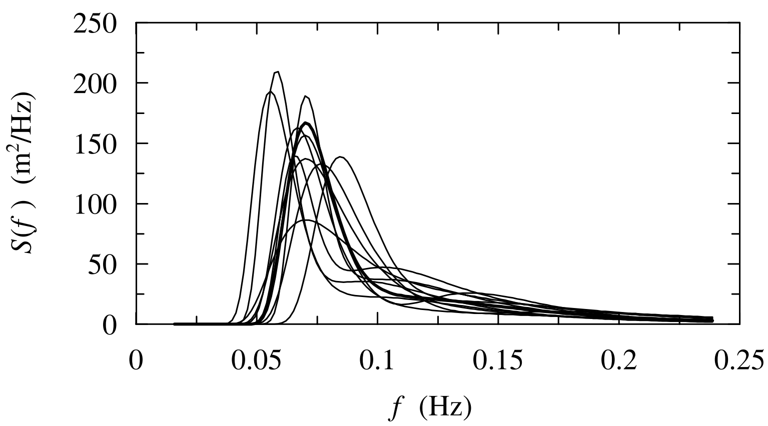


Table A.7 TMA spectrum.

Finite water depth.

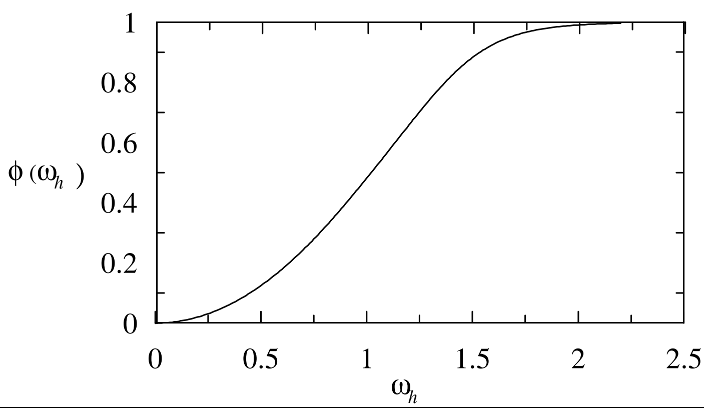
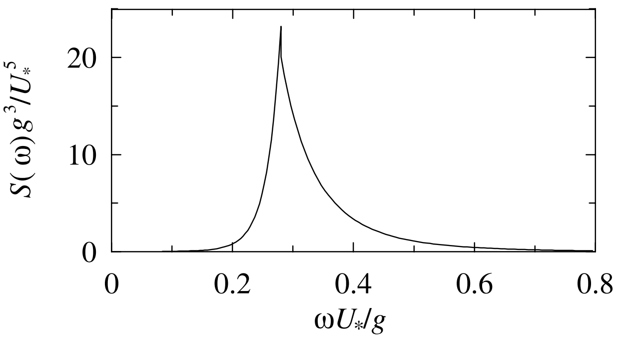
Input parameters	As for JONSWAP, and h
Spectral form	$S(\omega) = \alpha g^2 \omega^{-5} \exp\left[-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right] \gamma^{\exp\left[-\frac{(\omega-\omega_p)^2}{2\tau^2\omega_p^2}\right]} \phi(\omega_h)$, $\omega_h = \omega (h/g)^{1/2}$, $\phi(\omega_h) = \frac{k_h^{-3} \frac{\partial k_h}{\partial \omega}}{2 g^2 \omega^{-5}}$, $\omega^2 = g k_h \tanh k_h d$. Using the approximation $k_h^2 = \frac{\omega^2}{gh}\left(\omega_h^2 + \frac{1}{A}\right)$, $\phi(\omega_h) = 1 - \frac{1}{2} \frac{B\omega_h^3 + 3A\omega_h^2 + 2}{(A\omega_h^2 + 1)^2}$, where $A = 1 + 0.6522\omega_h^2 + 0.4622\omega_h^4 + 0.0864\omega_h^8 + 0.0675\omega_h^{10}$, $B = 0.6522\omega_h + 0.9244\omega_h^3 + 0.3456\omega_h^7 + 0.3375\omega_h^9$
$\phi(\omega_h)$	
Key reference	Bouws et al. (1985, 1987)

Table A.8 Mitsuyasu spectrum.

For limited fetch. The wind friction velocity U_* is usually assumed to be proportional to a measured wind speed.

Input parameters	U_* and F
Spectral form	$S(\omega) = 0$, for $\omega < 0.3\omega_p$ $S(\omega) = 9.12\times10^{-10} g^2\omega^{-5} \exp(3.55\hat{F}^{0.312} U_* \omega/g)$, for $0.3\omega_p < \omega \le \omega_p$ $S(\omega) = 0.589 g^2\omega^{-5} \hat{F}^{-0.308}$, for $\omega \ge \omega_p$. $\hat{F} = gF/U_*^2$
Spectral peak frequency	$\omega_p = (g/U_*)(5.76 - 0.201\log_{10}\hat{F})\hat{F}^{-0.312}$
Spectral plot for $\hat{F} = 10^4$	
Key reference	Mitsuyasu (1972)

The Specialist Committee on Waves

Committee Chair: Dr. Carl-Trygve Stansberg (MARINTEK)
Session Chair: Prof. Robert F. Beck (University of Michigan)

I. DISCUSSIONS

I.1. Discussion on the Report of the 23rd ITTC Specialist Committee on Waves: Application of JONSWAP Spectral Function to Wave Data Analysis for Storm 149 from North Alwyn

By: Yanying Wang, Jiwen Xu, Liang He, Dalian University of Technology, China

The data is from the North Alwyn platform in the northern North Sea and was recorded during a long storm in November 1997 (Wolfram, 1997). The data comprise surface elevation measurements in meters at 0.2 second intervals for whole period of the storm from one altimeter. Each sample contains 20 minutes (6000 data) of the time series and the data contains 409 samples.

1. Spectral Analysis

The FFT arithmetic is used to make analysis for the data and JONSWAP formula suggested by ITTC (2002) is taken into account to be basic of the comparison. The energy spectral density functions for real data with 409 samples are shown in Figure I.1.1 by using the FFT arithmetic.

Spectral moments may conveniently be used to characterize a spectral distribution. In general the n-th spectral moment is defined as shown in Figure I.1.2.

It can be found that the storm was beginning at 07:33, 16/11/97 and wearing away at 01:25, 22/11/97. At 21:30, 18/11/97 the storm reached the peak state.

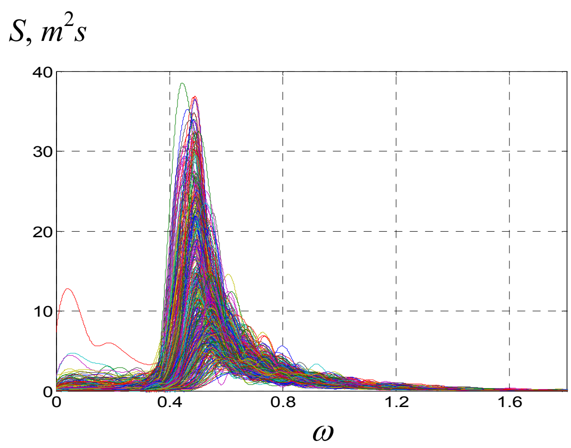


Figure I.1.1 The energy spectral density functions for real data with 409 samples.

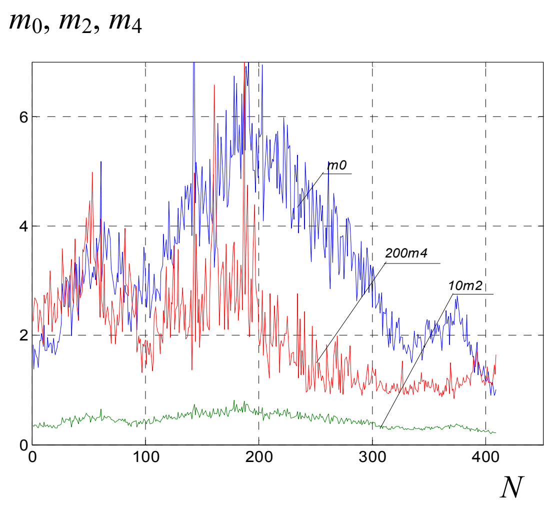


Figure I.1.2 The spectral moments m_0, m_2, and m_4 for real data with 409 samples.

The significant wave height for each sample is drawn in Figure I.1.3, in which the maximum one is more then 10 m.

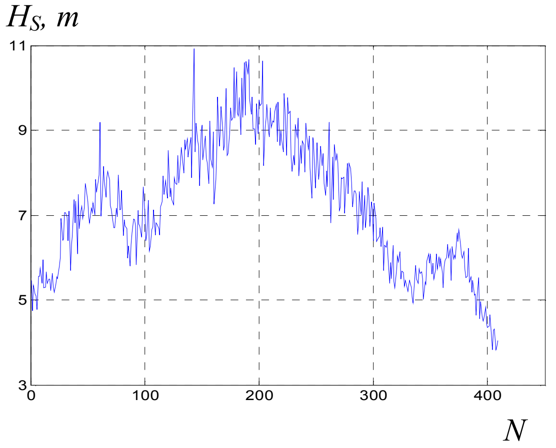


Figure I.1.3 The significant wave height H_S for real data with 409 samples.

Based on the statistical values of measured data from FFT arithmetic the following optimized parameters are given as expressing in Table I.1.1.

Table I.1.1 Parameters for JONSAWP formula.

Terms	Optimized	Standard
γ	3.27	3.3
$T_1\times\omega_P$	5.0	4.85
σ_A	0.07	0.07
σ_B	0.09	0.09

The energy spectral density functions are calculated by using the JONSWAP formula in Figure I.1.4.

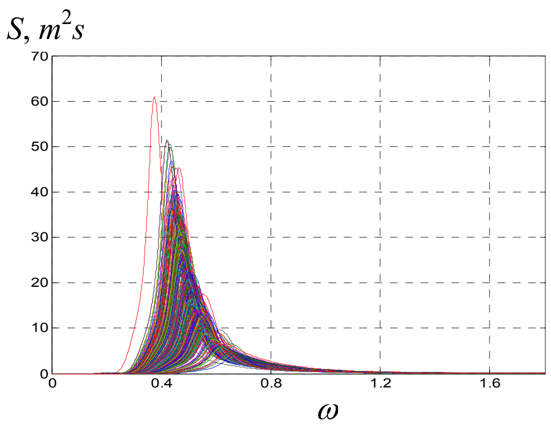


Figure I.1.4 The calculated energy spectral density functions for real data with 409 samples.

The significant wave height for each sample is also given in Figure I.1.5.

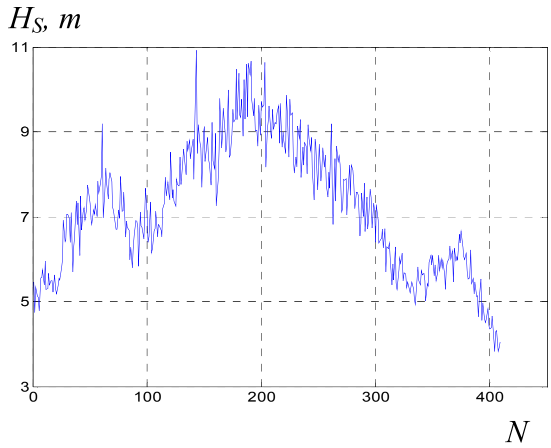


Figure I.1.5 The significant wave height H_S for computational results with 409 samples.

2. Comparisons

A comparison between results both from FFT arithmetic and from JONSWAP formula is listed in Table I.1.2, in which the significant wave height, peak frequency, and wave period are included. In the case of the peak state the energy spectral density functions can be determined by FFT arithmetic and JONSWAP formula respectively as shown in Figures I.1.6 and I.1.7.

The procedure to obtain the optimized parameters for JONSWAP formula is designed according to the objective functions, which are keeping equivalence in spectral area and peak frequency.

Therefore a good agreement is concentrated to the significant wave height and peak frequency only (see Table I.1.2).

Table I.1.2 Comparison of results.

Variables	FFT	JONSWAP
H_S, m	10.14	10.16
ω_P	0.4687	0.4512
T_1, sec	11.06	11.14

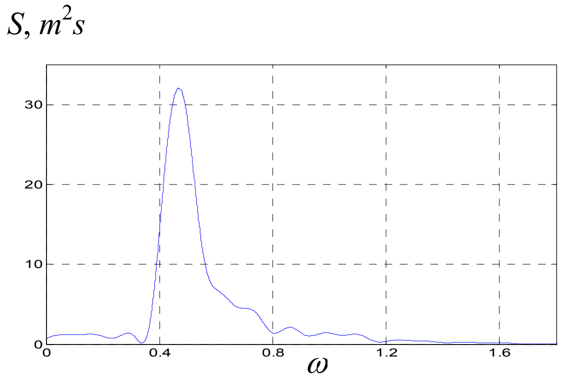


Figure I.1.6 Spectral density functions of the peak state from measured result.

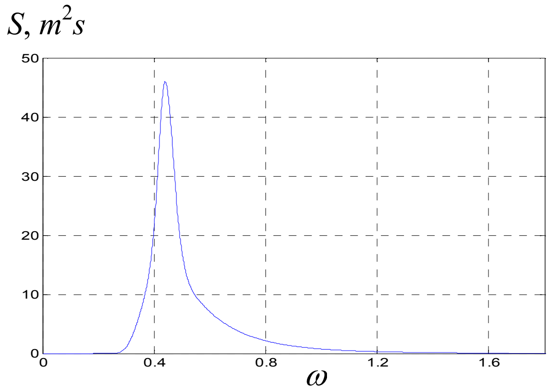


Figure I.1.7 Spectral density functions of the peak state from calculated result.

3. Suggestions

The observation data of waves is very useful to examine the wave spectrum, especially some of them from working platforms in certain sea area. All of parameters for spectrum should be constantly corrected in the engineering practice. A suggestion is that ITTC and its member institutions should pay attention to collect and to analyze wave real data from operative practice.

References

Wolfram, J., 2001, "Storm Wave Data from North Alwyn. Academic exchange letter from the SCW", 23rd ITTC, November 2001.

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I.2. Discussion on the Report of the 23rd ITTC Specialist Committee on Waves: On the introduction of ω^{-4}-type new wave spectrum

By: Tsugukiyo Hirayama, Yokohama National University, Japan

As described in the chapter 5 and useful Appendix A of the 23rd ITTC Waves Committee report, the standard ocean wave spectra are used in the naval architecture and ocean engineering field more than 30 years. Among those spectrum, the ω^{-5}-type spectrum (called as Pierson-Moskowitz (PM) Spectrum) is basic. That means the high frequency range or equilibrium range by the wave breaking is proportional to ω^{-5} in spectrum formulation. For example, so called fetch-limited JONSWAP Spectrum belong to the PM-type, because the peak value is enhanced based on PM-Spectrum.

In recent years, from the laboratory and field observations, it has been suggested that the shape of spectrum is ω^{-4}-type instead of ω^{-5}-type in the high frequency range (Toba, 1973; Phillips, 1985; Toba, 1997, 1998). The 23rd ITTC Waves committee report refers this fact. Before this, considering these results, the technical committee of ITTC recommended to investigate the effect of this type of spectrum on the responses of ships and offshore structures (ITTC, 1999). ω^{-4}-type wave spectrum seems to give more severe effects to the fatigue and acceleration problem comparing to the effects by using the ω^{-5}-type spectrum, but the quantitative effect on responses are not clear.

In this discussion, after introducing the ω^{-4}-type new formulation of wave spectrum, comparative investigations with ω^{-5}-type spectrum are introduced about the deviation of mean wave period, short-term and long-term predictions of vertical bending moment and vertical acceleration of a typical fine ship and full ship, following to the recent results by Hirayama et al. (2002).

At first, the conventional PM-Spectrum expressing the significant wave height H ($=H_{1/3}$) and mean wave period T ($=T_{01}$) is as follows:

$$S(\omega):\mathrm{PM}=171.44\frac{H^2}{T^4\omega^5}\exp\left(-\frac{685.76}{T^4\omega^4}\right)(\mathrm{m^2 s}) \qquad (1)$$

In the next, a new T1-spectrum (T is abbreviation of Prof. Toba) is defined as follows [formula (2) and Figure I.2.1, T is changed from 4 s to 18 s]. Here, $H_{1/3}$ and T_{02} are adjusted to become the same as P-M spectrum. Namely T_{02}:T1=T_{02}:PM and then T_p:T1 and T_{01}:T1 become different from T_p:PM and T_{01}:PM for the given values of H and T.

$$S(\omega):\mathrm{T1}=12.675\frac{H^2}{T^3\omega^4}\exp\left(-\frac{246.06}{T^4\omega^4}\right)(\mathrm{m^2 s}) \qquad (2)$$

In the third, T2-spectrum is defined as next formula (3) and Figure I.2.2. This case, $H_{1/3}$ and T_p are adjusted to become the same as PM type. Here, T_p is the peak period of the spectrum. So, T_p:T2=T_p:PM but T_{01}:T2 and T_{02}:T2 are not equals to T_{01}:PM and T_{02}:PM. for the given values of H and T.

$$S(\omega):\mathrm{T2}=23.126\frac{H^2}{T^3\omega^4}\exp\left(-\frac{548.61}{T^4\omega^4}\right)(\mathrm{m^2 s}) \qquad (3)$$

For the case of considering the dynamic responses having resonance phenomena, the peak frequency becomes most important. So, if we want make comparison with PM type spectrum, formula (3) will be preferable for the ship or floating bodies having resonance frequencies.

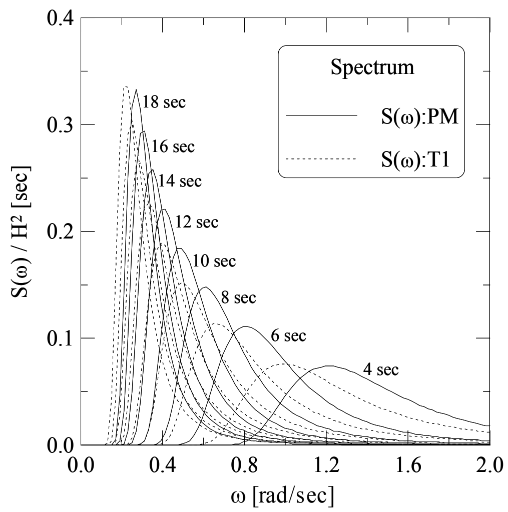

Figure I.2.1 PM and new T1 Spectrum.

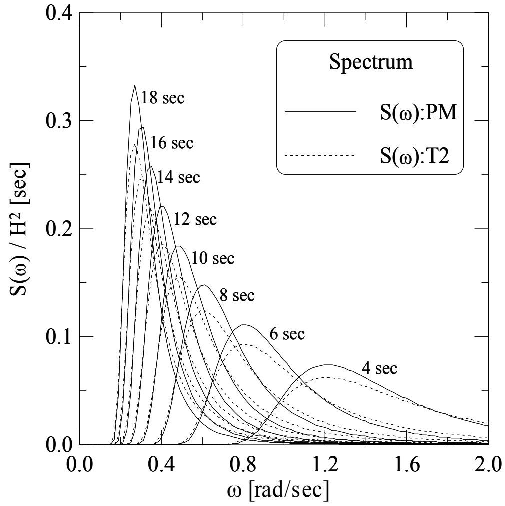

Figure I.2.2 PM and new T2 Spectrum.

After carrying out some calculations, following common results were obtained. The adopted ships are fine container ship (L_{PP}=138 m) and full ship (L_{PP}=250 m) and the adopted phenomena are short and long term predictions of vertical bow acceleration and mid ship wave vertical bending moment.

1) In considering to T_{24} (corresponds to peak to peak values), in case of T2-spectrum, maximum 16% increase of the number of encounter wave occurs. This is important for the fatigue problem, but in case of the T1 spectrum, encounter number is a little decreased.

2) Concerning to the short term prediction, about 6% reduction of maximum value was seen both in T1 and T2 spectrum.

3) About the long term prediction, both new spectra resulted 5% reduction at the exceedence probability of 10^{-8}.

Those results seem relatively common considering the process of long term prediction and result in some relaxation in design load etc., but further investigation is needed to obtain the more common conclusion. So, this problem is recommended to be discussed in 24th ITTC Ocean Engineering and Seakeeping Committees.

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Phillips, O.M., 1985, "Spectral and statistical properties of the equilibrium range in wind-generated gravity waves", Journal of Fluid Mechanics, Vol. 156, pp. 505-531.

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Hirayama, T., Choi, Y.-H., and Hirakawa, Y., 2002, "Introduction of ω^{-4} Type Wave Spectrum and the Brief Consideration of its Effects on the Long-Term Predictions", Journal of The Society of Naval Architects of Japan, Vol. 191, pp. 149-158 (in Japanese).

I.3. Discussion on the Report of the 23rd ITTC Specialist Committee on Waves: Wave spectrum formulas

By: Hyun-Soo Shin, HMRI, Korea

The ITTC standard wave spectrum formula has been well used in the field of model test and analysis of seakeeping. However, as the accurate description of waves is required in the offshore engineering for the optimum design, ITTC spectrum is only seldom used practically. Peakedness and bi-modal peak are special features to be emphasized in the practical engineering, which are not implemented in the current ITTC spectrum.

For example, the west African offshore is dominated by the swell from the south compared to wind driven waves. The swell of this sea is reported to be well described by the Ochi-hubble spectrum. Even though wind waves are not significant, the responses to wind waves are still important in the aspect of workability or fatigue damage ratio. In the field where swell and wind waves exist at the same time, it is required how to combine two environments in the numerical analysis and the model test. A unified spectrum to describe swell and wind waves simultaneously may be developed.

As the responses are not linear, the simple combination of swell and wind waves may give too conservative responses or opposite results. It is proposed that ITTC recommend a standard general formula of wave spectrum beyond the current ITTC spectrum. Or the standard numerical combination methods of swells and wind waves can be recommended by ITTC including the methods to perform the model tests in co-existing swell and wind driven waves.

I.4. Discussion on the Report of the 23rd ITTC Specialist Committee on Waves: "Freak Waves"

By: Hisaaki Maeda, Nihon University, Japan

I would like to ask three questions:

1) Has the Committee discussed about the definition of "Freak Waves"?
2) Two terminologies "Freak Waves" and "Rogue Waves" make us confused. Has the Committee discussed this issue?
3) Has the Committee discussed about the probability of occurrence of "Freak Waves" which may depend on the steepness parameter of the JONSWAP waves according to a recent investigation?

I.5. Discussion on the Report of the 23rd ITTC Specialist Committee on Waves: Spectral Parameters Governing the Efficiency of Directional Wave Focusing

By: Keyyong Hong, KRISO, Korea

The superposition of different wave components and resultant focusing wave is important because it plays a significant role in many ocean processes and it may also impose extreme forces on ocean structures. The laboratory study on wave focusing has been mainly devoted to two-dimensional case. However, since the real sea is essentially directional, its directional characteristics should be considered in simulation of focusing wave fields. We developed an effective directional wave focusing technique which can be applied serpent-type wavemaker system, and the effects of dominant parameters that govern the focusing efficiency of generated directional waves are investigated.

The wave packets for generating the three-dimensional focusing waves in directional wave basins can be represented by the double summation model as

$$\eta(x,y,t)=\sum_{i=1}^{N_f}\sum_{j=1}^{N_\theta}a_{ij}\cos[k_i(x-x_b)\cos\theta_j+k_i(y-y_b)\sin\theta_j-2\pi f_i(t-t_b)] \qquad (1)$$

where a_{ij} is the amplitude of component wave with the ith frequency f_i and jth direction θ_j, k_i the wave number and (x_b, y_b, t_b) the focusing location and time. N_f and N_θ are the number of the frequency and direction, respectively. It shows that the surface wave elevation of focused wave packet depends on the focusing location and time and the associated component wave parameters of amplitudes, frequencies and directions.

Since the direction of each component wave should be adjusted for focusing of waves at a specific location, the directionally focused wave fields can be described by the frequency spectrum and the directional range of wave packet ($-\alpha$, α) instead general directional spectrum. Two simplified frequency spectra, which make the control of generated wave characteristics easier, are frequently used for wave focusing (Takezawa & Hirayama, 1976). The first one is called constant wave amplitude (CWA) distribution where the wave amplitude of each component wave a_{ij} is constant. The second kind of frequency spectrum is called constant wave steepness (CWS) distribution where the component wave steepness $k_i a_{ij}$ is constant. So the component wave amplitudes a_{ij} for CWA and CWS distributions can be expressed as a function of focused wave crest amplitude A, respectively

$$a_{ij}=A/(N_f N_\theta)\,,\quad a_{ij}=A/(N_\theta k_i\sum_{i=1}^{N_f}\frac{1}{k_i}) \qquad (2)$$

when the wave amplitude for each frequency is supposed to be distributed uniformly over the directional range.

Assuming the water depth h and introducing the center frequency f_c and the frequency bandwidth Δf, the generated focusing wave fields are completely defined by following parameters (Hong et al., 2002)

$$\eta=f\,[N_f, N_\theta, A, f_c, \Delta f, (x_b, y_b), t_b, \alpha, h] \qquad (3)$$

If N_f and N_θ are big enough, a continuous spectrum can be approximated and the effect of N_f and N_θ can be neglected. Also, we can neglect the parameters of water depth and focusing location and time by choosing them constants considering basin features. Then, the directional focusing wave packet is governed by directional range α and characteristics of frequency spectrum.

From the linear multidirectional wave maker theory (Sand & Mynett, 1987; Takayama, 1984), the wave signal packets to generate focusing waves can be calculated by the following equation representing the relationship between the wave board signals and the generated waves at the position of wave makers.

$$S(n,t)=\sum_{i=1}^{N_f}\sum_{j=1}^{N_\theta}\frac{a_{ij}}{T(f_i,\theta_j)}\sin[k_i nD\sin\theta_j-(k_i x_b\sin\theta_j+k_i y_b\cos\theta_j)-2\pi f_i(t-t_b)] \qquad (4)$$

where n is the serial number of wave boards counted from the right to the left and $S(n, t)$ is the stroke signal for nth wave board which has a breadth of D. $T(f_i, \theta_j)$ is the hydraulic transfer function between the wave maker stroke and the water elevation at the wave maker that can be calculated by the following equation for piston-type wave makers.

$$T(f_i,\ \theta_j)=\frac{4\sinh(k_i h)\left[\sinh k_i h-\sinh k_i h_m\right]}{\cos\theta\left[2k_i h+\sinh(2k_i h)\right]} \qquad (5)$$

where h_m is the wave maker elevation.

Based on numerical and experimental investigation (Hong et al., 2002; Hong & Liu, 2002), the spectral parameters governing the characteristics of generated directional focusing waves (Figure I.5.1) were analyzed in terms of focusing efficiency as follows:

1) The characteristics of directional focusing wave packets strongly depends on the directional spreading function of wave field as well as the center frequency, width and shape of frequency spectrum.

2) As the wave packet approaches to a focusing point, the wave energy increases significantly in the high frequency band (Figure I.5.2) and it is primarily contributed by directional focusing and enhanced by the energy transformation from low frequency components. The wave packet spectra disperse again downstream.

3) The smaller center frequency usually results in the larger maximum wave amplitude since it is stronger in linearity and it makes effective for wave focusing, while the larger frequency width enhances the wave focusing (Figure I.5.3). The focusing efficiency is more sensitive to the frequency width than center frequency. Also, the narrower angular focusing results in larger focusing amplitude than the wider one.

4) The surface elevation induced by CWS spectrum model is higher than corresponding one by CWA spectrum model. Also, the wave front of CWA is steeper than that of CWS. This implies that the focused waves by CWA method are easier to break.

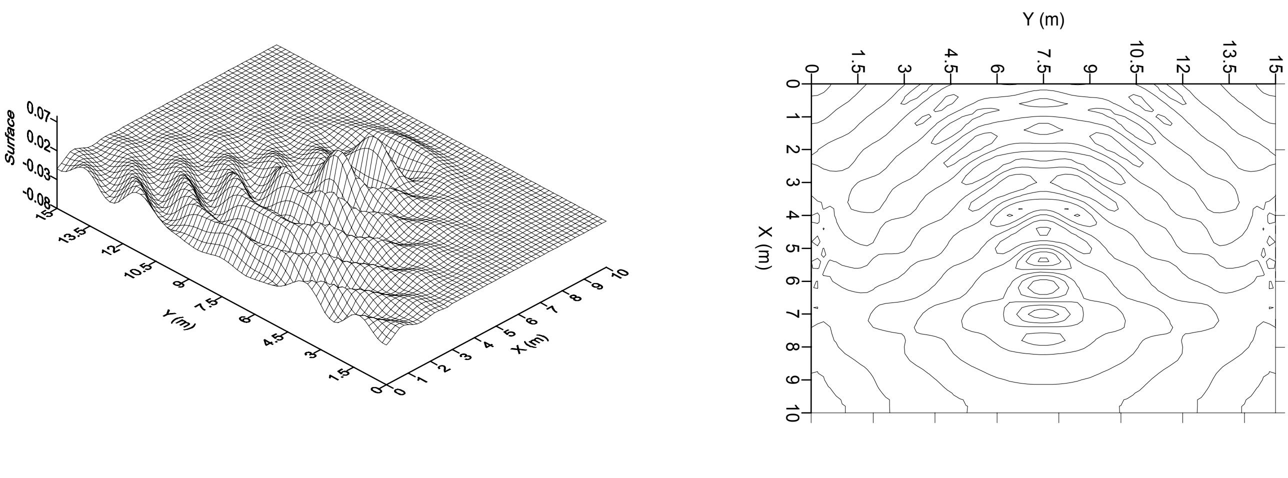

Figure I.5.1 Generation of a directional focusing wave field.

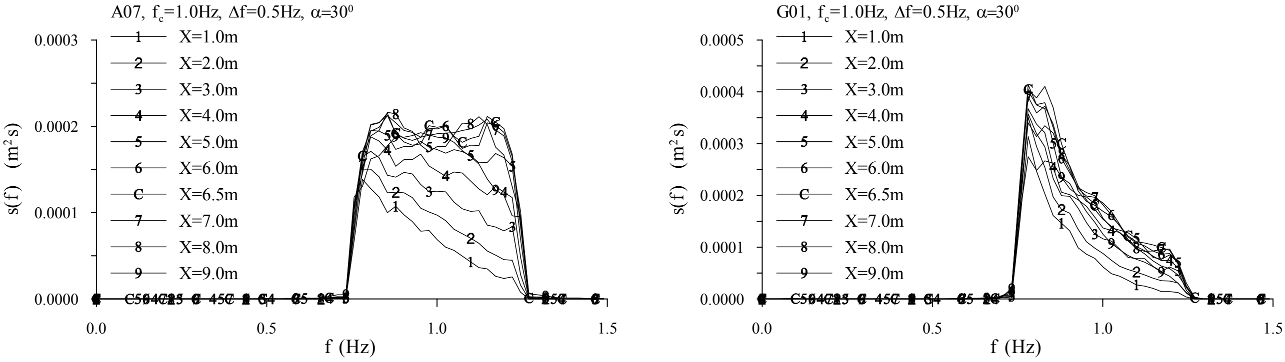

Figure I.5.2 Spectrum variation along the centerline for CWA and CWS model.

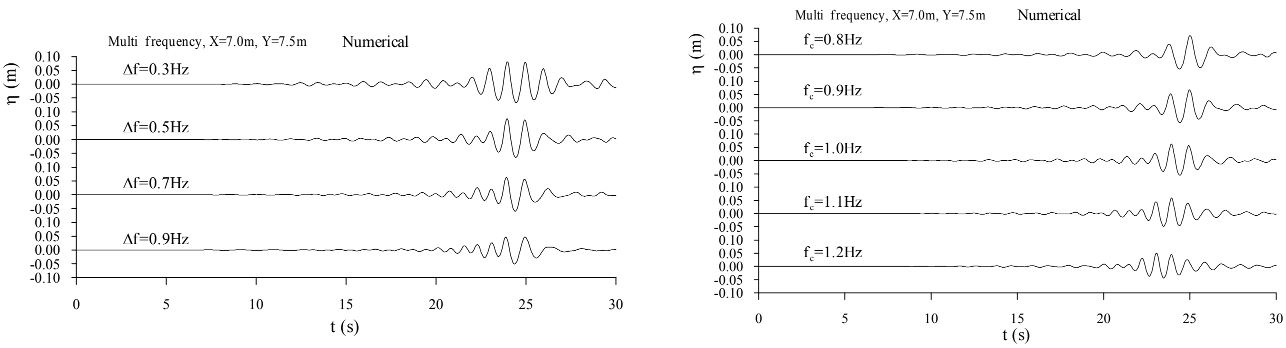

Figure I.5.3 Effects of center frequency and bandwidth on directional wave focusing efficiency.

References

Hong, K., and Liu, S., 2002, "The directional characteristics of breaking waves generated by the directional focusing in a wave basin", Proceedings of 21st OMAE, OMAE2002-28072.

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Takezawa, S., and Hirayama, T., 1976, "Advanced experimental techniques for testing ship models in transient water waves: Part II. The collected transient water waves for using in ship motion tests", Proceedings of 11th Symposium on Naval Hydrodynamics, 37-54.

I.6. Discussion on the Report of the 23rd ITTC Specialist Committee on Waves: "Quality" of waves

By: David C. Murdey, NRC, IMD, Canada

What guidance can the Committee give to help facilities decide "how good" the waves need to be to model a particular situation?

What "quality" of waves is acceptable?

I.7. Discussion on the Report of the 23rd ITTC Specialist Committee on Waves: Deterministic seakeeping tests

By: Günther F. Clauss, Technical University of Berlin, Germany

Congratulations for this excellent report. I appreciate very much that the committee supports the application of deterministic seakeeping tests. We are developing this technique as a tool for the investigation of wave/structure interactions, using tailored wave packets embedded in irregular seas (Clauss, 2002a). Wave elevation, pressure distribution as well as acceleration and velocity fields in space and time can be determined at the position of the structure, even if the vessel is moving at an arbitrary speed and course. Thus physical mechanism of vessel dynamics can be evaluated as a cause-effect chain. Composing reponse based wave sequences special phenomena such as capsizing of ships can be analysed in detail. Based on such seakeeping tests non-linear numerical models are developed and verified to design safer ships and optimize ship operation and navigation (Clauss et al., 2002a).

The technique also allows the generation of registered wave sequences like the extremely high New Year Wave which has been recorded on January 1, 1995 at the Draupner field in the North Sea (Figure I.7.1). Using our dedicated generation technique the non-linear genesis of these wave groups can be studied. Also, the seakeeping behaviour of any structure can be evaluated in such extreme environment. As shown in Figure I.7.2 the semisubmersible GVA 4000 has been tested in these extreme waves investigating heave, pitch and airgap (Clauss et al., 2002b). Selected wave groups can be tuned arbitrarily and integrated in regular or irregular seas, e.g. by stretching or compressing the peak wave to adjust a critical wave length and steepness for response based evaluations. Also phase relations between incident wave and (moving) structure can be varied, and any test can be repeated identically if a specific effect is analysed.

As a consequence, with this technique the mechanism of non-linear behaviour of ships and offshore structures in tailored waves can be evaluated which helps to reveal the mechanism of arbitrary wave/structure interactions including slamming, green water and capsizing as well as other survivability design aspects (Clauss, 2002b). It is also indispensable for the development and validation of (non-linear) numerical programs which are necessary tools for systematic investigations of seakeeping characteristics of marine systems in harsh environment.

References

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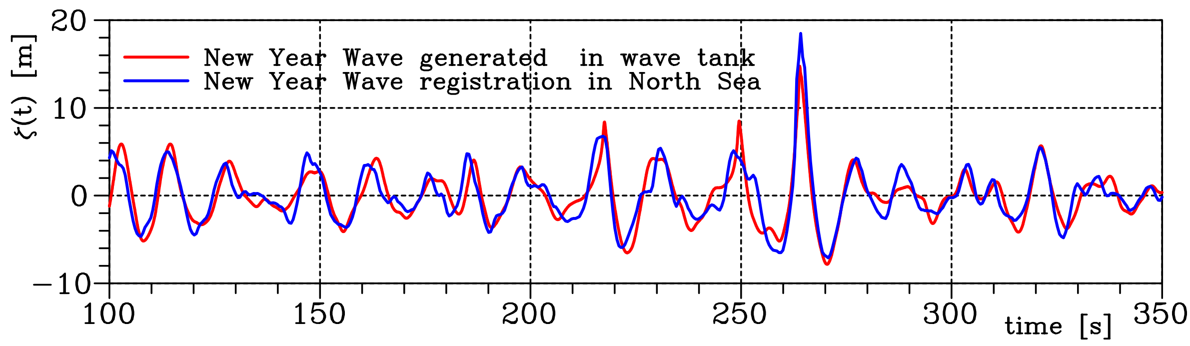

Figure I.7.1 Comparison of model wave and registered New Year Wave, presented as full scale data.

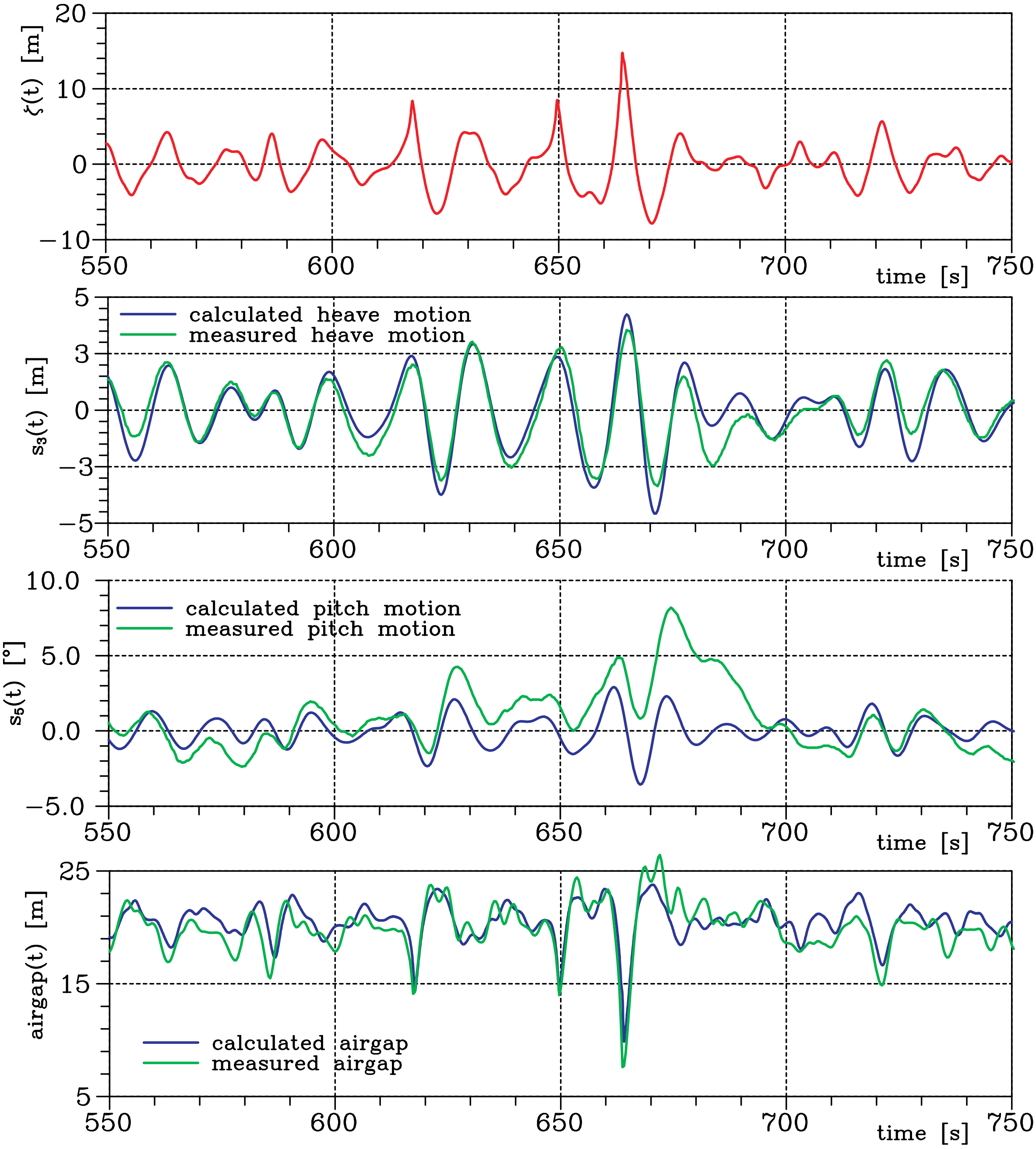

Figure I.7.2 Results of numerical simulation and experimental tests for semisubmersible GVA4000: Heave, pitch and airgap (measured at scale 1:81, presented as full scale data).

I.8. Discussion on the Report of the 23rd ITTC Specialist Committee on Waves: The algoritm Fourier Transform Proper (FTP)

By: Michael Schmiechen, Germany

Please let me mention a basic problem of 'craftsmanship'. Spectra and power spectra are usually determined from finite sets of sampled data. Consequently unacceptable systematic truncation errors, classical uncertainty, may be encountered, if FFT algorithm are applied without scrutiny. These errors, particularly in spectral peaks and tails, can be avoided, if auto-regressive models are being employed.

The errors mentioned may be acceptable in 'quick and dirty' work, but in scientific investigations it is certainly of importance to base conclusions on correctly determined spectra. The algorithm FTP (Fourier Transform Proper) has been published in Schiffstechnik 1999 and is to be found on my website. For routine applications, if any, the algorithm may need to be optimized for speed.

II. COMMITTEE REPLIES

II.1. Reply of the 23rd ITTC Specialist Committee on Waves to Y. Wang

This discussion is an interesting one seen in light of the spectral shape models treated in Chapter 5 and in the Appendix of our Report, and is also a reminder that real storms are time-varying. The problem of a model reproduction of a full storm is addressed. (We are not sure whether or not the analysis presented was intended for further time-series reproduction, or whether it was a purely spectral analysis task). One procedure, which is followed here, is to match the spectral parameters H_S and T_p for each 20-minutes sample. These are normally considered the main parameters, and are reasonable first choices for this type of analysis.

The matching of the shape (through the γ in the present single-peaked JONSWAP model) is also of interest. In the present analysis, it seems that a constant $\gamma = 3.27$ (denoted as "optimized" in Table I.1.1) is applied throughout the whole storm. The optimizing procedure applied is not discussed. If one compares the two spectra in Figures I.1.6 and I.1.7, the shape matching does not seem to be optimal, and for the total study it would probably have been better if the γ was optimized for each 20-minutes sample? (The bandwidth of the spectral smoothing applied in Figure I.1.6 might perhaps have affected the apparent spectral shape?). One could also raise the question whether or not the single-peaked JONSWAP model is always the optimal model, although it does not seem to be too bad in this case although some low-frequency contribution is apparent in the analysis of the field data.

We agree in the conclusion that the ITTC should pay attention to the collecting and analysing of real wave data, which is an important input to the modelling activities. A close contact with industry and oceanography/meteorological agents on this topic is important to achieve this.

II.2. Reply of the 23rd ITTC Specialist Committee on Waves to T. Hirayama

As the Discusser is pointing out, recent field and laboratory observations indicate that the tail of the ocean waves spectra seems in many cases to follow a ω^{-4} shape, rather than the commonly used ω^{-5} shape. Some possible formulations are suggested. This certainly has effects on predicted loads on ships and offshore structures, and may therefore be important. We would, in addition to the literature referred to by the discusser, also mention the paper by Torsethaugen (1993), where observations from the Norwegian Sea indicate that the exponent N may vary with the sea state and on the sea type (wind sea or swell). Thus a definite decision on what is the correct answer may not exist universally, but may rather depend on the case. Therefore we recommend that further studies on more field data should be made to provide a more robust background for future spectral models.

References

Torsethaugen, K., 1993, "A two-peak wave spectrum model", Proc. of 12th OMAE Conf., **2**, Glasgow, Scotland, UK, pp. 175-180.

II.3. Reply of the 23rd ITTC Specialist Committee on Waves to H.-S. Shin

A need for a new standard ITTC wave spectrum formula is argued. There may be good reasons for that. However, we realize that there are several formulations in use today, not only the present ITTC spectrum, but also many others. What the SCW has done in the present Report on this topic, is to collect and present the most frequently used ones, for easy access and use by the ITTC community. We also found that the comparison between them is also interesting in itself. It is not obvious to us that having "one and only" formula is the optimum solution, but we think it is very important to model what is relevant for the actual situation (often defined by clients), and to document it properly. Recently, the including of swell has been found to be important in many cases. Therefore, the Ochi-Hubble spectrum is certainly a choice for use, as well as other formulations that are also in common use. We should also welcome the development and including of new and improved formulations.

II.4. Reply of the 23rd ITTC Specialist Committee on Waves to H. Maeda

The Discusser has raised three questions about "Freak Waves", and our answers are as follows:

1) The SCW has not discussed explicitly the definition of "Freak" waves, but a good definition could be "Unexpected waves". The notion should highlight that the event is beyond standard probabilistic predictions. In many cases this means that higher-than-second-order effects must be taken into account. The discussion in ISSC (2000) covers this topic quite well.

2) We have not tried to distinguish between "Freak Waves" and "Rogue Waves", and it is not discussed in the Committee. Sometimes, a better notation may be simply "Extreme waves".

3) The SCW has not discussed the probability of occurrence of "Freak Waves" in the ocean, or its dependency on steepness parameters, partly because this is believed to be a question more for ISSC than for ITTC, while the modelling of it is in the ITTC area. The topic is, however, important to follow up in future work on wave modelling.

References

ISSC, 2000, Proceedings of the 14th International Ship Structures Congress, Nagasaki, Japan.

II.5. Reply of the 23rd ITTC Specialist Committee on Waves to K. Hong

The possible directional characteristics of extreme waves at sea, its modelling, and its loading effects on structures, is a problem that still needs to be clarified and investigated in more detail. The discussion presented is an interesting contribution in this direction. Possibilities in laboratories with multidirectional wavemakers are illustrated, and some parameters that might be useful in defining cases for applications are shown. Numerical modelling by a linear approach is shown, and some conclusions based on them as well as on experiments are obtained. We suggest that a further development of the numerical model into a nonlinear formulation is carried out, since the local steepness in such extreme focussed events is expected to be quite high, and nonlinear effects may therefore be essential for the analysis. Furthermore, a comparison between characteristics in unidirectional and directional extreme waves, and their loading effects, would also be helpful. Field data documentation on the appearance of such events, as well as more research on resulting loads and responses, are also important in the future models are being employed.

II.6. Reply of the 23rd ITTC Specialist Committee on Waves to D.C. Murdey

The problem of defining the "quality" of wave modelling, and the accuracy required to obtain this quality, certainly needs to be further investigated. In Chapter 3 of our Committee Report, we have tried to highlight which wave parameters that might be essential or critical in various types of model test situations. Thus the "quality" needed depends on the application, and the generated waves should be benchmarked with respect to the actual parameters described for the given application. (See also our comment to Discussion Paper No. 7).

The quantification of the accuracy, or tolerance accepted, has not been a major issue in the Report. A brief overview of principles in the error analysis was presented in the Report of the 22nd ITTC Specialist Committee on Environmental Modelling. However, further work on this topic could be carried out through sensitivity studies (numerical and/or experimental) on actual structural model responses. A documentation of the repeatability of wave conditions/parameters in wave facilities is also recommended.

II.7. Reply of the 23rd ITTC Specialist Committee on Waves to G.F. Clauss

In our Report, we describe the "Transient Wave" technique as a technique in addition to regular wave and irregular wave generation. We consider it to have advantages and disadvantages, as we also have with the other two types of generation. Obvious advantages are that the reflection problems are reduced or avoided, and the running time is rather short. It is also, in principle, well-defined, although this may depend on how they are specified and documented, relative to the actual application. For parallel theoretical studies involving nonlinear numerical reconstruction of events, the short duration is also welcome.

In Chapter 3 of our Report, we highlight some important aspects to be addressed when applying the technique. These include the need to identify and specify (select) which critical wave parameters to be reproduced, and their documentation. The procedures required to select actual waves or wave groups still need to be thought through. This may depend on the actual application, and it is recommended that some more research should be carried out to clarify these parameters. The dilemma is: How do we know the statistical significance of the model wave actually generated? (The question raised by another discusser – Prof. Murdey in Discussion No. 6 – about the quality and accuracy needed in wave modelling, is perhaps very relevant in the specification phase in this case).

Various alternatives exist in the selection of wave events. The simplest approach is to generate a short wave train with a specified maximum crest (or wave) height. Another option is illustrated by the Discusser: One may try to reproduce events from field data, either based on point recordings of elevation, or more complete recordings including kinematics. An alternative approach suggested by others is to base the modelling on design tools such as the "New Wave" philosophy. Still another way is to calibrate "full" (e.g. 3-hour) sea states and pick out selected time windows from these for later use with the structural model. The latter method has the appealing feature that it preserves the random nature of the wave event (and some of its pre-history), without a need to identify and quantify all detailed characteristics of it.

II.8. Reply of the 23rd ITTC Specialist Committee on Waves to Michael Schmiechen

The use of straightforward FFT in spectral estimation has been commented by the Discusser. For cases with long time series (i.e. several hundreds of wave cycles or more) we think these problems are normally of minor importance, while for short records it may become quite relevant. We agree that the users should be careful in choice and use of methods (and verify their properties), and are grateful for the information about the published procedure.