REPORT OF THE PANEL ON VALIDATION PROCEDURES

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REPORT OF THE PANEL ON VALIDATION PROCEDURES

I. GENERAL

1. MEMBERSHIP AND MEETINGS

The Panel on Validation Procedures (the Panel) appointed by the 18th ITTC consisted of the following members:

Dr. W. C. Lin (Chairman), David Taylor Research Center, U.S.A.
Dr. G. van Oortmerssen (Secretary), Maritime Research Institute Netherlands, The Netherlands
Dr. M. E. Davies, British Maritime Technology Ltd., U.K.
Professor O. Faltinsen, Norwegian Institute of Technology, Norway
Dr. A. J. Haimov, Bulgarian Ship Hydrodynamics Centre, Bulgaria
Dr. Ph. Hocquet, Bassin d' Essais des Carènes, France
Dr. B. Della Loggia, CETENA, Italy
Professor K. Mori, Hiroshima University, Japan

Dr. G. van Oortmerssen was elected Secretary at the first Panel meeting in Kobe, Japan, immediately following the 18th ITTC.

Since the 18th ITTC, the Panel has met five times, as follows:

Paris, January 1988,
Columbia MD, June 1988,
Wageningen, January 1989,
Hiroshima, September 1989,
Genoa, January 1990.

2. RECOMMENDATIONS OF THE 18TH ITTC

The 18th ITTC established the Panel on Validation Procedures, with the following tasks:

- Issue a first outline of validation procedures, including uncertainty analysis, to the Technical Committees not later than September 1, 1988.

- Provide a common framework for the discussion of validation and uncertainty analysis, as applied to the various areas of work of the ITTC members.

- Outline standards for the points to be covered in a model validation. Such points include, but need not be limited to:

  describing the model approximations;
  providing confidence statements on the operation of the model;
  discussing evidence of model prediction correlation with full scale.

- Provide a consistent report to the 19th ITTC in 1990 on guidelines for validation with an example from each of the main areas of work of the ITTC members, ideally an example from numerical modeling and physical modeling in each area.

- Provide, on the basis of this report, a recommendation to the Full Conference on how guidelines can be implemented in terms of practical procedures to be used by the ITTC members in the day-to-day conduct of their business.

II. REVIEW OF RESEARCH ON VALIDATION PROCEDURES OF IMPORTANCE TO THE ITTC

INTRODUCTION

What is validation and why are we addressing it at this time in ITTC? This question has arisen on many occasions in the introduction of this topic to members of the ITTC community. It is an understandable reaction to an apparent questioning of accuracy and method of approach from experienced and careful engineers and researchers. The counter, of course, is that validation is what thorough workers have always addressed, but now the requirements are to reveal the steps taken to achieve that confidence and to provide a quantification of the resulting accuracy. Increasingly, a question being asked of professional engineers is: "What steps have you taken to ensure the quality of your work and what evidence can you provide to demonstrate a level of confidence in the result?" It is an issue in courts of law, in cost-benefit analysis for engineering projects, in safety and environmental impact appraisals, in performance guarantees, in comparative studies of different methods and in the competitive area of selling software and testing and consultancy services.

There are many benefits to be derived from uncertainty analysis and these can have both technical and economic benefits. A particular experiment may, for example, have no value in helping to differentiate between two designs if the uncertainty is too large. A worthless experiment may, therefore, be avoided by such an analysis, or the necessary guidance may be provided on which facets of the measurement/modeling must be improved. Equally, a relatively crude prediction may be entirely appropriate for a certain decision, providing a knowledge of the uncertainty involved is available in order for that judgment to be made. The emphasis in all these decisions is 'Quality/Accuracy for Purpose.' Only with some quantification and a formal analysis can informed choices be made by both ITTC members and, importantly, their customers. The formal methods employed are also valuable aids to communication. Not only should these methods lead to numerical statements, but they should also provide the necessary framework for discussion and exchange of ideas.

The work of the Panel reported here forms just the beginning of a continuing process to make 'validation' a more familiar and overt activity. At this time, many other engineering disciplines are grappling with aspects of error estimation, uncertainty and validation. Activity is evident in the aerospace and nuclear industries and in the international standards organizations, and therefore this is a particularly opportune time for ITTC to take up the challenge on behalf of marine and hydrodynamic interests. The report describes the approach adopted by the Panel, followed by reviews of the existing literature (for both measurement and computational methods). This leads to Section 3, in which the report concentrates more specifically on ITTC applicability. The Guidelines for Measurement and Computation (Section 3) are followed by specific examples in Section 4 and the Conclusions and Recommendations in the final sections. At various points in the text, the vocabulary of validation and uncertainty analysis is introduced. It is appropriate, however, to outline briefly in advance the manner in which the words are used.

- 'Validation' refers to the total process of confirming that the estimate (model test, numerical calculation, full-scale measurement, test-rig measurement, data base prediction, etc.) is properly related to the true value of the parameter in question. Validation includes all aspects from modeling assumptions, through measurement techniques and numerical methods to the production of the final estimate (see description of the 'total process' in the Validation Working Group report of the 18th ITTC).

- 'Uncertainty Analysis' is the means of quantifying and expressing 'how valid' the method (measurement, calculation, etc.) is in estimating the required true value. A complete Uncertainty Analysis would define the probability distribution that the error (true value - estimate produced by the method) could take. Inevitably, it will often be necessary to deal with 'partial' validation and uncertainty analysis applied to only parts of the total method. Such activities may be perfectly acceptable providing the basis and assumptions are clearly defined.

- 'Verification' is to be used in a specific way to describe checking that a particular requirement in the method is implemented correctly. In computational methods its use is to be confined to checking that the code correctly performs the solution of the chosen equations by the chosen technique.

1. APPROACH ADOPTED BY THE PANEL

The 19th ITTC Validation Panel was formed with tasks set out as follows:

- Assess available methods to quantify uncertainty in physical and numerical modeling.

- Agree with Technical Committees on a number of specific examples to be subject to uncertainty analysis.

- Provide specific guidance to Technical Committees on suitable methods.

- Recommend to the 19th ITTC minimum standards on the definition of validity of predictions.

At the outset of the work of the panel, the existing literature, guidelines, and international standards were assembled and reviewed (see Section 2). With respect to the second task, the Panel sent letters to all of the Technical Committees in February 1988 to express its wish to arrive at, with the cooperation of respective Technical Committees, a number of specific examples that could be subject to uncertainty analysis during the course of the 19th ITTC. The Panel further indicated its interest in addressing aspects of model testing, full-scale measurement, and numerical modeling and requested the Technical Committees' input and assistance in this regard.

In accordance with the recommendations given to the Panel on Validation Procedures established at the 18th ITTC Full Conference, the Panel prepared an interim "Guidance to Technical Committees of the 19th ITTC on the Application of Procedures to Access Uncertainty in Measurement and Prediction." This 'Guidance' explains the objective, background, methodology for analysis and calculation of uncertainties (or errors), and accuracy analysis in numerical predictions. In addition, its appendix contains two examples of uncertainty analysis for a resistance test and a computational prediction of 3D diffraction/radiation of waves. Finally, a note on the validation of Computational Fluid Dynamics (CFD) is also included in the appendix. The 'Guidance' was mailed to the chairmen of all the Technical Committees and the Secretariat in October 1988 for review and comments. The Panel recommended that each Technical Committee consider inclusion of the validation procedures in its work and expressed the Panel's eagerness for cooperating with them on the subject matter. In general, most of the Technical Committees' responses to the Panel's recommendation were positive but cautious, indicating that more time was needed to embrace such a subject matter in their committee work. However, some committees indicated strong interest in cooperating with the Panel to work on actual problems pertaining to their respective fields. Results of such cooperative efforts, specific examples of application of uncertainty analysis, are included in Section 4 of this report, while others can be found in the reports of some Technical Committees.

The Panel also undertook some 'missionary' actions. Authors of papers for the 5th International Conference on Numerical Ship Hydrodynamics (in Hiroshima, September, 1989) were encouraged to address explicitly the issue of accuracy analysis of their results. An account of the accuracy analysis efforts in the papers of this Conference is given in Section 2.3. In addition, a half-day Workshop on Validation of CFD was organized under the auspices of the Panel in conjunction with the Conference in Hiroshima. During this Workshop, ideas were exchanged on how to ascertain the accuracy and reliability of predictions of physical phenomena by numerical methods. Based on the interaction with Technical Committees, the experiences with the 5th International Conference on Numerical Ship Hydrodynamics and the discussions during the Workshop in Hiroshima, the initial Guidance to Technical Committees has been updated. The final version of these guidelines is presented in Section 3.

2. REVIEW OF RELEVANT LITERATURE

2.1 Measurement Uncertainty and Validation

A significant body of published literature exists on the

subject of measurement uncertainty and its assessment. A flavor of the background to the development of an internationally acceptable methodology is given by Abernethy and Ringhiser (1985). They indicate some of the history and names behind the development of the ASME-SAE-AIAA-ISO standard on 'Measurement Uncertainty Methodology' and also describe the numerical experiments (Monte Carlo simulations) performed to 'validate' the statistics of the methodology itself. By no means is all the work recent. Important contributions were made by Hersey (1913), and major activity was commenced by ASME Performance Test Code Committees in the 1950's following Kline and McClintock (1953). In particular, in association with ASME, Kline, Moffat, and Abernethy have been consistent workers in the field for many years. In 1983 and 1987, ASME's Fluid Engineering Division held symposia on 'Uncertainty Analysis' and 'Experimental Uncertainty in Fluid Measurement' and the proceedings, Kline (1985a) and ASME (1987), provide a comprehensive background of history, philosophy and illustration by examples.

Kline's paper from the 1983 meeting, Kline (1985b), is entitled "The Purposes of Uncertainty Analysis" and deals with concepts, definitions and questions of applicability. He distinguishes between the usage of the words 'error' and 'uncertainty' and provides a sound basis of nomenclature that can be adopted elsewhere. (Kline's definitions have been adopted in the definitions in the INTRODUCTION). He goes on to provide 'case histories,' that are practical examples of value and wide applicability of 'Uncertainty Analysis,' and include: avoiding a 'worthless' experiment, improving the design of a velocity probe, increasing the sensitivity of a measurement system, improving a computer model by careful attention to the design of an experiment to provide empirical coefficients for the model, and allowing a better comparison to be made between theory and measurement. The paper is recommended to engineers new to the concepts and is suggested as a good introduction to be read prior to considering the standards documents themselves (summarized in Section 3 of this report).

It is evident from the papers of Kline, Abernethy, and Moffat that an element of struggle has existed over the years in trying to establish 'measurement uncertainty' standards. In spite of a landmark paper in 1953, Kline and other advocates were still writing 'missionary' papers in the 1980's. The need to convince and persuade remains today. The logic of the argument is undeniable, but the task is not always easy and significant discipline is clearly required. Many of the same messages are provided by Moffat (1985, 1988). In the former paper, he concentrates on uncertainty analysis at the PLANNING stage of an experiment. He uses the example of a convective heat transfer experiment to demonstrate how the method can help to differentiate between two measurement and analysis techniques for the experiment, and therefore improve the likelihood of a successful outcome. In doing so he underlines that, although any measurement process will have many sources of error, in practice relatively few terms dominate. The error propagation analysis will help determine these and allow concentration on the aspects that are important. An excellent way to perform the error propagation is by numerical means, with the SAME computer program that is used for the data reduction and analysis for the experiment. Moffat emphasizes and illustrates this approach in both papers. In his 1988 paper, he also pays attention to the difference between uncertainty in 'single sample' measurements (the subject of Kline and McClintock (1953)) and in 'multiple sample' experiments. Many complex flow definition measurements are in the former category, as, of course, are most tests conducted for engineering assessment. Clearly, a difference exists in the ability to build a statistical base, though even in 'single sample' tests related historical statistics can exist.

Smith and Wehofer (1985) claim that the most significant advances in aeroengine test facilities have derived from comprehensive measurement uncertainty analyses. They stress how the framework of uncertainty analysis has led to better communication and discussion, to greater credibility and confidence in the results, and to more cost-effective operation through informed choices for hardware, software and program tasks.

Most of the material in the ANSI/ASME domain would appear to relate to engines, thermo-turbines, flow measurement and general thermo-fluids. Standards exist for Gas Turbine Measurements, ISA Handbook (Abernethy and Thompson (1980)) and for Flow Rate Measurement, ISO (1983), while the general ANSI/ASME Performance Test Code, ANSI/ASME (1985), comprehensively deals with the principles and calculation procedures for flow rate and compressor and steam turbine performance. The concept of Performance Test Codes (e.g., ANSI-measurement of shaft power, rotary speed, density, viscosity), covering uncertainty analyses for specific measurements, may provide a model for ITTC to adopt in dealing with the question of Validation and Uncertainty Analysis. In addition to the standard reference material contained in the ANSI/ ASME domain and the ISA/ISO Handbooks already mentioned above, there are also a number of text books that are helpful to students of this subject. The book by John R. Taylor (1982), "An Introduction to Error Analysis," is written for use with an introductory college course in experimental physics. This book provides a clear exposition of subject matters such as: Preliminary Description of Error Analysis, How to Report and Use Uncertainties, Propagation of Uncertainties, Statistical Analysis of Random Uncertainties, and the Normal Distribution.

Another publication helpful especially to the user of the ANSI/ASME standard on Measurement Analysis is a recent book by Coleman and Steele, Jr. (1989), "Experimentation and Uncertainty Analysis for Engineers." This book covers much of the same material as in Taylor's book at a more practical level and emphasizes the methods of applying the uncertainty analysis to the planning, debugging, and execution of experiments. The book is also unique in that the estimation and propagation of both **precision** (random or repeatability) errors and **bias** (systematic or fixed) errors are considered, as opposed to the previous practice of assuming that the bias errors are negligible or have been eliminated by calibration. The book further discusses the procedures for handling both the small sample sizes requiring use of the so-called 'Student's t distribution' and the important practical cases in which bias errors in different variables are correlated.

2.2 Uncertainty Analysis for Full-Scale Ship Trials -- A Literature Review

2.2.1 Foreword. To define the errors that affect the results of full-scale trials, the situation is substantially

similar to that of model experiments. However, for full-scale trials the degree of difficulties involved is greater and a considerable financial commitment is required to conduct experimental tasks that meet scientific criteria, mainly because of the large number of parameters to be monitored. In spite of this, some significant work was carried out as far back as the fifties on the fundamental experiments by BSRA for the 'Lucy Ashton,' Denny (1951) and Conn et al. (1953); and on Professor Aertssen's campaigns of experiments for ships in service, Aertssen (1953 and 1955). These experiments featured for the first time a precise definition of experimental errors. Over the following years, procedures began to consolidate and the evolution of instruments made it possible to perform the speed-power measurements during delivery trials with increasing confidence, as documented by the Codes of Procedure, BSRA (1964) and SNAME (1952).

The impression, however, that these practices have not become as widespread as they could, prompted the 18th ITTC Powering Performance Committee to collect and present in its committee report the answers to a questionnaire on error assessment during full-scale testing using the different instruments and methods adopted by the various institutions. The results presented at the time indicate that the test procedures adopted by some organizations were not standard. Therefore, there were considerable discrepancies in the error assessment, Della Loggia and Lauro (1987). For this reason, it was felt that benefit could be gained by reanalyzing the results of these assessments for an in-depth investigation to determine an appropriate approach to be followed for assessing experimental errors in standard tests of the ship's speed, propeller rpm and shaft torque during delivery trials.

2.2.2 Uncertainty Analysis for Non-Repeated Measurements. It is well-known that the theory of errors provides a rigorous definition of the magnitude of experimental errors for repeated measurements of a single parameter. In normal practices of sea trials, however, one must deal with the problem of determining the extent of the errors of a set of non-repeated measurements. Because of time or the impossibility of reproducing the same trial conditions, in many tests measurements of even the important physical quantities are not repeated. In such cases, it is necessary to know the measuring consistency of the instrument(s) used for the trials in order to estimate the probable experimental errors.

For direct measurements the maximum absolute error depends exclusively on the precision of the instrument. In the more frequent case of indirect measurements, the physical parameter to be investigated is a function of the measurements of several directly measured physical quantities:

$$y = f(u,v,.....). \qquad (2\cdot2,1)$$

The maximum absolute error Δy of y will thus be a function of the measurement errors of the respective primary parameters, Δu, Δv,...,etc. If we assume that the errors Δu, Δv, are sufficiently small to allow powers greater than one, as well as their cross products (for example $\Delta u \cdot \Delta v$), to be neglected, the maximum error will be given by:

$$(\Delta y)^2 = \left(\frac{\partial f}{\partial u}\Delta u\right)^2 + \left(\frac{\partial f}{\partial v}\Delta v\right)^2 + ..., \qquad (2\cdot2,2)$$

where $\partial f/\partial u$, $\partial f/\partial v$,.... are the partial derivatives of the function f with respect to its independent variables u, v, ..., etc. The maximum relative error is then given by:

$$\left(\frac{\Delta y}{y}\right)^2 = \left(\frac{1}{y}\frac{\partial f}{\partial u}\Delta u\right)^2 + \left(\frac{1}{y}\frac{\partial f}{\partial v}\Delta v\right)^2 + ... \quad . \qquad (2\cdot2,3)$$

2.2.2.1 Power measurements. This type of approach was used by several authors, Hine (1973) and Martinelli et al. (1971), to define the accuracy of torque measurements, obviously with different results depending on the type of torquemeter used. In this instance, the need for a standard definition of error is evidenced by the works of Journee et al. (1980) and Di Lorenzo (1989) in which different assessments of errors were presented for practically identical torquemeters. In addition to the torque errors, the shaft rpm measuring errors also have to be considered. However, the rpm contribution to the total error is generally considered less important because it is an order of magnitude smaller than that of the torque, according to the evaluations reported by Hine (1973), Martinelli et al. (1971), Journee et al. (1980), and Di Lorenzo (1989). Lastly, great care must be exercised to add to these assessable errors the bias errors which, as shown in literature, are normally underestimated or neglected. To limit the extent of these particularly elusive errors, a sound engineering check of the data and thorough and repeated calibration of the instruments are always recommended.

2.2.2.2 Speed measurements. The measurements of interest are those of speed through the water, although the present practice is to measure the speed of the ship over the ground and to use some form of analysis procedure to eliminate the effects of any current. Ship position and, hence, speed over the ground can be measured to a high degree of accuracy with some commonly available microwave or satellite position-fixing systems. Another method commonly used in the past employed a specially constructed measured mile course. The advantage of using an accurate position-fixing system is that trials can be carried out in almost any location, whereas the only advantage of the measured mile course is that no special equipment need be installed aboard the ship. The references, Nizery (1969), Jourdain (1968), and Sitzia et al. (1972), among others, describe a series of trial devices based on several microwave range position-fixing systems. The results indicate that ship speed over the ground can be measured to better than 0.1 knots. For this reason, the major cause of speed errors is the correction for proper account of the influence of waves, wind, and current. A sound approach to this kind of correction is given by Jourdain (1964) where two or three runs on opposite directions are required according to the estimated characteristics of the current during trials: constant or linearly variable in time.

2.3 Validation and Verification of Numerical Methods

2.3.1 Overview of CFD Validations. Computational Fluid Dynamics (CFD) is a much younger activity compared to scale model and full-scale measurements. This is reflected in the limited amount of information that can be found in the literature on the topic of

accuracy analysis and validation of CFD. Most of the ideas that the Panel found helpful in formulating guidelines for our field have come from other areas, in particular the aeronautical and nuclear industries.

In May 1988, the Advisory Group for Aerospace Research & Development (AGARD) organized a Symposium on Validation of Computational Fluid Dynamics, AGARD (1988). This symposium was followed by the Panel with particular interest, because it was expected that the state-of-the-art of validation of CFD in the aerospace world was more advanced compared to the field of ship hydrodynamics. Therefore, the ITTC community might benefit from methods and ideas developed in the field of aerodynamics. From this point of view, the contents of the Symposium were rather disappointing. Two invited papers were presented, Bradley (1988) and Marvin (1988), both of which discussed validation philosophy as a topic. Although they said a great deal about the importance of CFD, interaction with experimental work and the role in the design process, very little was mentioned about the process of validation itself. Among the other papers there were only two that addressed the validation philosophy as a topic and attempted to provide a methodological framework, Boerstoel (1988) and Heckmann (1988). Most papers did not address the issue of validation at all, but described progress in numerical flow description and showed examples of results and comparisons with (wind tunnel) measurements. A few authors showed effects of mesh size or time step variations and some described special experiments used for validation.

In the aircraft industry, it is common practice to perform extensive flight test programs for certification of new types of aircraft. In this respect, one should expect flight test data to be used as an important base for validation. This, however, was not evident in the papers presented at the symposium. Only two papers, Voogt et al. (1988) and Sutton et al. (1988), discussed comparisons of flight test data with computational results. Several papers mentioned large international co-operative projects with extensive tests in various facilities to provide a data base of 'benchmark' experimental data that can be used for validation purposes. The ITTC community should seriously consider pursuing similar efforts.

The assessment of the value of the conference that was given in the official evaluation report, Sacher (1989), was very much in line with the observations given above. In the summary of the report, the main conclusion is worded as follows: "This ambitious aim (of the symposium) was reached only to a degree by comparison of experimental and computational data. But at least some of the papers have attempted to validate computer codes by the use of recently developed 'data bases' providing also detailed information on 3D-flow field characteristics."

Some of the conclusions are worth quoting here:

"- The experimentalist and the theoretician are coming more and more together.

- Numerical and experimental flow simulation are more and more understood as complementary tools, (no replacement of the wind tunnel).

- The process of 'code validation' is often misunderstood as a 'comparison' of computed and measured data.

- More emphasis should be devoted to understand disagreement between computed and measured results. In some cases the agreement was too perfect!"

In Newman (1989), the author presented a personal view of the present and future status of numerical ship hydrodynamics. In this paper, much attention is paid to the validation of CFD. Newman focused the discussion on two particular problems of inviscid flow without vorticity or circulation, viz., wave resistance in calm water and ship motions in waves at zero forward speed. Newman made a distinction between validation of the theory, generally by means of experiments, and validation of the computational model. The use of an experimental comparison to serve simultaneously both purposes seems attractive, but uncertainties in the experimental results and limitations of the theory mask the detection of numerical errors and inaccuracies. In Newman's view, a program should be tested to a tolerance of between four and six decimals on a variety of aspects, including:

comparisons with established benchmarks;
verification of reciprocity and other analytic relations such as the Haskind relations; and
tests to confirm that the results converge to the estimated tolerance as the number of panels or other discretization elements is increased.

An example is discussed of validation of programs for linear harmonic motion in waves of a body in a fixed mean position, based on the comparative effort carried out by the ISSC for a Tension Leg Platform, Eatock Taylor and Jefferys (1986). Convergence as well as comparisons with other similar programs and a time-domain program are discussed.

Within the nuclear industry, extensive and detailed guidelines have been established for the verification and validation of scientific and engineering computer programs ANSI/ANS-10.4 (1987). In these guidelines, a distinction is made between validation and verification. If a computer program is to be developed to represent a process or phenomenon occurring in nature, the usual approach is to represent this process or phenomenon in terms of a mathematical model. This model is used as the basis for program design. The design in turn is converted into a set of computer instructions. Verification can be considered to be the proof or demonstration that the computer instructions correctly represent the design, and that the design correctly represents the mathematical model. Validation, on the other hand, is the demonstration that the verified computer program (and by inference the mathematical model) are an adequate representation of the natural phenomena. The guidelines emphasize that, although validation and verification activities may be conducted on existing programs, they are most effective when carried out parallel with program development. A parallel approach allows for early detection and correction of errors in the software requirements, design and coding. Much attention is paid to a systematic and structured approach, in which the software development process is subdivided into the following phases:

Initiation or concept exploration phase.
Requirements definition.
Design.
Coding.
Integration and testing.

Installation.
Operation and maintenance.

For all these phases, the appropriate validation and verification activities are described. Readers should note that other quality assurance standards for software (e.g., NATO AQAP13 and British Standard 5750) do not specifically permit retrospective attention to validation and verification.

Aspects of the uncertainty of numerical methods are discussed in a monograph by Michlin (1988). Four types of errors are distinguished in the numerical process: approximation error, distortion error, algorithmic error and round-off error. CFD creation and validation problems in aerodynamics and aircraft research are discussed in papers, Belotzerkovskiy and Kulifeev (1982) and Belotzerkovskiy et al. (1984), where the regression analysis method and least-squares procedure are used. Examples are given showing a methodology to quantify the results from validation of computational procedure by a proper comparison based on statistical methods with experiments. Some consideration on validation problems and their impact on ship hydrodynamics application at BSHC are presented in Bogdanov and Haimov (1987). Some professional journals have adopted a policy of not accepting papers reporting numerical solutions unless systematic error testing and accuracy estimation had been undertaken. In this respect, reference is made to the editorial statement in the Journal of Fluids Engineering, Roache et al. (1986), which was quoted in the Report of Advisory Council Working Group on Validation (18th ITTC, Volume 2, 1987).

2.3.2 Validation Carried Out in the INC5 Papers. Although there is no commonly accepted method for carrying out a systematic accuracy analysis, the paper committee of the 5th International Conference on Numerical Ship Hydrodynamics (INC5, held on 24-28 September, 1989, in Hiroshima Japan) asked all the authors to discuss explicitly their accuracy analysis, such as effects of grid and/or time steps. Convergence check and/or pilot computations for less complicated cases are also recommended. The following report is a survey of how the authors carried out the CFD validation in their papers in response to the above request.

2.3.2.1 Survey of papers. The methods of accuracy analysis may differ according to the specific numerical methods, such as finite difference method or boundary element method. However, most papers carried out accuracy analyses and described their analyses quantitatively or qualitatively. Some of the papers contain accuracy analyses that are sufficient to make readers convinced of their computed results. Most of the papers described the computational conditions such as grid size, number of panels, number of iterations, and so on. Some, but not many, gave information about CPU time or memory size that helped considerably for readers to understand the scope of the computing code.

The analyses reported in the papers were diverse. They can be roughly categorized into several groups as follows: (Some typical papers, identified by authors within square brackets, are cited in each category.)

- Calculations were carried out for geometrically simpler cases and the dependence of the results on the grid number or convergence was examined [Kodama] [Kashiwagi] [Wu] [Jensen] [Aanesland] [Kinnas].

- Similar to the foregoing, the flow conditions were different from the final computations [Doi] laminar, [Bai] two-dimensional progressive waves without body, [Kashiwagi] zero-advancing speed, [Kubota] without cavity.

- Physical conditions such as mass imbalance or conservation were examined [Masuko] [Bai] [Ertekin].

- Some computed results of important variables under different computing conditions were shown, and the dependency of the results was examined [Cointe] [Suzuki] [Cheng] [Chen] [Zhao] [Yasukawa].

- Final results computed under more than one condition were shown together in comparison [Kodama] [Hino] [Kinoshita] [Wu] [Musker].

- Comparisons of the final results were made with other computed results [C. Yang] [Bai] [Choi], with analytical solution [Sen] [Bai], or with experimental results [C. Yang] [Piquet].

- The dependence of the results on the expression of the boundary conditions was examined [Hoekstra] [Suzuki].

In some cases for which the computing codes had already produced ample results through various applications, either the explicit descriptions of the analysis were not given [Cheng] [Stern] or only their previous papers were referenced for the analysis [Oh]. In some papers, only a statement about having performed the analysis was made but without actual results [Choi] [Moshkin] [Falch]. They all showed the comparison of their final results with the experiments. Some papers described candidly that some problems still existed in their results. One author stated that the removal of the filtering scheme caused a very large stern wave to force the computations to be aborted [Ertekin]. Another author described that the results had not yet attained the steady state due to the huge amount of computing time required [Zhu]. Such frank descriptions should not amount to a discredit of the results. Rather, they should be welcomed by the readers in gaining a sound understanding of such results. Two papers devoted a section under the heading of 'accuracy analysis' [Hino] [Cointe]. It demonstrates a good way to address the accuracy analysis in a positive and explicit manner.

2.3.2.2 Summarizing comments. It is not meaningful to ask merely which method is best for CFD validation without further qualification, because the answer may depend upon whether a code is still in its infancy or near completion. The answer may depend also on the purpose of the validation, such as, investigating the numerical techniques, numerical simulation methods, or using the developed code to gain understanding of physical phenomena.

In any case, there ought to be a consensus of opinion that computational conditions should be described as precisely as possible regarding the grid size, computing domain, and so on. If possible, a description of computing time and memory size should also be included. A description of the convergence is absolutely necessary. Such a description

should enlighten the reader concerning the state of the computation. Pilot computations for simpler cases are essential to accuracy analysis, although they do not guarantee the outcome of the final results. Some common examples may be recommended, such as a back-step flow for turbulent flow simulations, flow around a vertical circular cylinder among the incident waves for radiation problems, flow around the Wigley model for ship wave and flow problems, and so on. These are helpful preliminary investigations for further complicated flows.

2.3.2.3 Concluding remarks. When the policy of requiring an explicit description of systematic accuracy analysis for the Conference papers was first discussed, there was some negative feeling because of concern over imposing unnecessary burdens on authors without a real prospect of accomplishing something concrete. However, in hindsight, the policy made a significant difference to the overall quality of the Conference papers. Certainly, accuracy analysis would have been carried out by the authors even without such a policy requirement. However, the policy must have prompted the explicit and concrete discussion of the computational accuracy issues by most authors. Such explicit discussion of the accuracy issues is essential to sound understanding of the paper by readers.

Because issues concerning the CFD validation are complex and diverse, it is difficult or even inappropriate to confine the methodology of accuracy analysis to a single manner. In other words, each CFD validation may call for a particular method that is most suitable for its circumstance and purpose. Nevertheless, the experience of the INC5 showed that any accuracy analysis is better than no analysis. Thus, a conclusion may be drawn that a moderate standard of accuracy analysis, such as that required by the INC5, should be adopted by the authors of CFD papers, or at least by such authors in the academic and research communities. Perhaps a practical way to start such a trend is to require the authors to devote a section on accuracy analysis in their papers.

2.3.3 FPS 2000-Comparative Study. In Norway a comparative study of computational methods for estimating the motion responses of floating structures in waves was organized in 1989. The project has been sponsored by NTNF (Royal Norwegian Council for Scientific and Industrial Research) and Norwegian oil companies, 23 institutions from all over the world having contributed to the comparative study. A deep draft floater and a turret-moored production ship were chosen for the comparative study. In general, the first order predictions agreed well, while there was an order of magnitude discrepancy in the predicted slow drift motions. Verification of 3D diffraction/radiation programs and sources of errors were addressed. The errors were differentiated into human and numerical errors. It was demonstrated that human errors were the major source of discrepancies. This means some of the results were erroneous due to: wrong scaling, wrong constants, wrong wave direction, wrong mirroring in generating panels, data format errors, misunderstanding of coordinate systems and phase definition. Three sources of numerical errors were identified, namely, panelling of the body surface, Green function calculation, and solution of the equation system.

Thus, the attention of the project became focused on the need for verification procedures and benchmark tests for computer programs. It has been recommended that several standard print-outs and checks should be made to ensure the quality of computed results. Among these are: check of stiffness matrix, natural periods, asymptotic values, stability check of moored system in wind, current and waves, numerical free oscillation tests, etc. Furthermore, a recommended practice/guide for computations should be worked out.

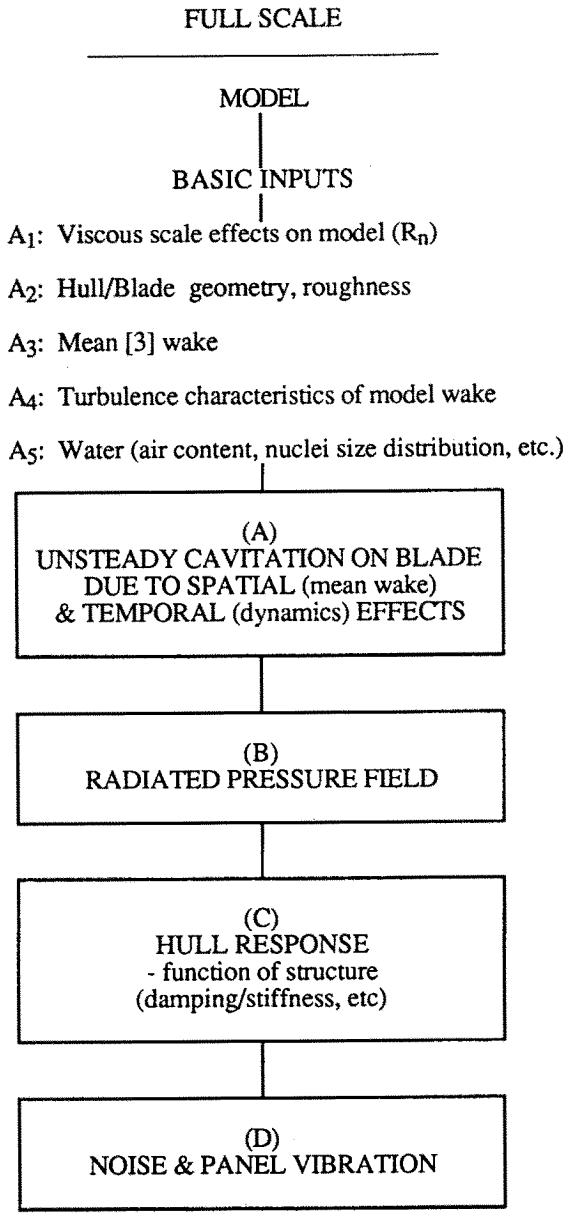
3. APPLICATION TO ITTC WORK AREA

3.1 Foreword

It is evident from the general nature of the material reviewed in Section 2 and the opening statements in the INTRODUCTION, that no engineering activity, aimed at producing practical results and guidance for application, is exempt from the need to address seriously the question of the accuracy of its predictions. Certainly, in an ideal world vigorous attention to uncertainty and validation is required in every part of ITTC's work (in both 'academic' and 'practical' fields). The uncertainty and validation principles (and algorithms) are common to all disciplines, but each and every 'prediction' will have a different set of potential error sources and varying sensitivity to uncertainty in basic parameters. Model measurements are easiest to address, especially with the systematic application of commonly used 'data reduction programs.' These can be used to produce influence coefficients numerically, therefore avoiding at times difficult analytic differentiation. Correlation with full scale and judgments on 'how valid was the model experiment?' become more complex, involving more overall 'validation' in addition to 'uncertainty analysis.' Note that full-scale measurement is not 'correct' in an absolute way. Measurement uncertainty clearly exists in all cases; on many occasions full-scale trials are particularly prone to error. Complex numerical solutions presently prove the most difficult with which to deal, though progress is being made and some of the same principles apply. There are, however, very few good examples. Demonstration of applicability and meaning of concepts is often best done by example, and this is covered in Section 4.

Gradually, a catalogue of standard analyses of representative tasks could be built up by ITTC. Members could then use these uncertainties providing they assured themselves that their own procedures resulted in the same basic elemental accuracies as used in the standard analysis or that they inserted their own uncertainties into the equations derived in the standard analysis. Such an approach could suggest to a member organization the aspects of a particular test or computation upon which it should concentrate if it wished to reduce uncertainty in the results.

Validation assessment methods can also be used to formalize some of the more difficult modeling of physical phenomena with which ITTC is involved. As an illustration, the sensitivity of the results of a test to uncertainty in the input conditions may be dictated by particularly complex fluid mechanics, which may be difficult to replicate at model scale. An example for discussion is cavitation-induced hull pressure fluctuations.



Item (D), Noise and Panel Vibration, is clearly a complicated function of the variables (A_i), (B), (C_i), and generally far beyond our capability to deal with analytically. However, some empirical estimates (from parametric studies) may be made of $\partial B/\partial A_i$, $\partial D/\partial C_i$, $\partial D/\partial B$, etc. and these could be combined (in a simplistic way, no doubt) using the standard uncertainty procedures. Then a similarly 'formal' look is required to determine how the (A) variables are modeled in different organizations' experimental methods and how uncertain these are in relation to full scale. This has to include consideration of how well-known are full-scale parameters. For example, what is the accuracy in determining the nominal wake? How good is the process of measuring a wake in a towing tank, then applying a scaling to the ship Reynolds number? What accuracy can be expected from CFD predictions of ship wakes? Are any reliable full-scale measurements available to prescribe the input wake?

The complete task is, of course, awesome and precision is very difficult. Nonetheless, it does become easier to imagine investigating the discrepancies in predictions of (D) (or more usually (B)) by such an approach, and, at times, to demonstrate the validity of using certain test methods for, as an example, comparison of designs, even though absolute values may be highly uncertain.

In all the applications of validation discussed, it is necessary to agree and use a common framework and vocabulary. It is strongly recommended that, in this respect, ITTC follows the existing guidelines already contained in the documentation of the international standards organizations.

3.2 Guidelines for Uncertainty Analysis of Measurements

3.2.1 Objective. For any measurement, the aim is to construct an uncertainty interval within which the true value (by definition unknown) will lie with a chosen confidence (usually 95 percent).

3.2.2 Background. The recommendations to ITTC follow the lines of the ISO/ANSI (Section 2) standard.

3.2.3 Outline of Methodology

3.2.3.1 Types of error. Only two types of error exist in a well-controlled activity: **precision** errors (random or repeatability), and **bias** errors (systematic or fixed). We need only add to the discussion that, in general, it is presumed that major mistakes and malfunctions are absent from data subject to such scrutiny. If such errors do exist they may, of course, contribute grossly to the two types of error and may well render the exercise meaningless. Monitoring of data and engineering judgment may be necessary to eliminate such errors, but this must be rational and not just careless discarding of 'rogue' or 'outlying' data points. Care is needed under the second type if it is known that the limits of bias error are not symmetric.

3.2.3.2 Defined measurement process. A detailed analysis of error sources is necessary for the particular measurement process under study. The uncertainty interval may well vary when calculating differences (e.g., in comparing different designs of propeller or hull) from that achieved when making absolute measurements or comparing different processes (e.g., physical model test vs. numerical prediction). The final uncertainty result relates to that process alone, even though much of the ground work (e.g., precision of certain basic steps) may be common to many measurement exercises.

3.2.3.3 Combining error estimates to create the resultant uncertainty intervals. The stages are:

a) identify all error sources (there will be many!);
b) determine (statistically and by judgment) the individual precision and bias errors for each element in a) (Phases A and B);
c) determine the sensitivity of the end result to the error sources in a) (derive error propagation coefficients) (Phase C);
d) create the total precision uncertainty interval from c) and b) (Phase D);
e) create the total bias uncertainty interval from c) and b) (Phase E);
f) combine d) and e) by either addition or 'root sum

square' methods (Phase F); and
g) declare the results of d), e), and f) separately.

3.2.4. Calculation Methods

3.2.4.1 Phase A - elemental precision estimates. The object is to determine the precision index, S, of a particular elemental error source. S is an estimate of the standard deviation of the scatter that would be obtained if the measurement x were repeated a number of times. If an end result is influenced by k elemental measurements, $x_i(i=1,k)$, then at this point the object is to estimate the value S_i that accompanies x_i. Combining the k error sources follows later. If the basic measurement x_i can be repeated N times, then an estimate of the true standard deviation (only obtainable from an infinite set of measurements), usually called the 'experimental standard deviation', is available from

$$S_i = \sqrt{\sum_{j=1}^{N} (x_{ij} - \bar{x}_i)^2 / (N-1)}, \qquad (3\text{·}2,1)$$

where $\bar{x}_i$ is the average of the N measurements.

The larger the value of N, the more accurate S_i will be, i.e., the greater the number of degrees of freedom, ν_i.

$$\nu_i = N - 1 \text{ for an estimate of standard deviation.}$$

In a particular test or prediction a single value of x_i may be used (with S_i being available from previous experience) or the actual value of x_i used may be an average of a number of points, P. The precision improves if averages are taken, thus

$$S_{i(average)} = S_{i(single)}/\sqrt{P}. \qquad (3\text{·}2,2)$$

If S_i is estimated at the same time as $x_{i(average)}$ is formed, then P = N. If single samples are used P = 1, and S_i must come from separate information.

Output of Phase A:

$$S_i = S_{i(single)}/\sqrt{P} \text{ , and} \qquad (3\text{·}2,3)$$

ν_i = the number of degrees of freedom for S_i.

3.2.4.2 Phase B - elemental bias estimates. The basic independent measurements x_i discussed in 3.2.4.1 above may have a bias error in addition to the precision errors estimated by Phase A. Unfortunately, this error type is not amenable to statistical analysis. Remember that all known offsets and corrections that can be applied are assumed to have been implemented, so only residual unknown bias errors remain. Examples might include: the accuracy to which calibration coefficients can be calculated and applied; the precision with which zero settings can be made; perhaps the knowledge that a mean measurement (say force or pressure) may be biased by the intensity of fluctuation (but having no direct measurement of the intensity); and, straying into a computational area, perhaps the knowledge that a particular integration or grid-based calculation tends to consistently under- or over-estimate the true value. The limits to this bias error should be estimated with a 'confidence' that is equivalent to 95 percent confidence, i.e., the estimator would bet with odds of 20:1 that the error had been covered. (Note - the literature stresses that a normal human failing is to underestimate the size of these errors).

Output from Phase B.

Bias limits $\pm B_i$ for symmetric bias errors,
or separately B_i^+ (3·2,4)
and/or B_i^-, if the sign of the bias is known.

3.2.4.3 Phase C - propagation of errors: influence coefficients. The k potential sources of error x_i (i=1,k) were introduced in Section 3.2.4.1. The final result of the test or prediction R is seen as a function of the k independent variables x_i,

$$R = R(x_1, x_2, \ldots x_k). \qquad (3\text{·}2,5)$$

For a small error ε_i in x_i the Taylor expansion gives

$$R(x_i + \varepsilon_i) = R(x_i) + \varepsilon_i(\partial R/\partial x_i) + \varepsilon_i^2(\partial^2 R/\partial x_i^2)/2! + \ldots \; . \qquad (3\text{·}2,6)$$

Therefore, the error in the result

$$R(x_i + \varepsilon_i) - R(x_i) \approx \varepsilon_i \, \partial R/\partial x_i \quad \text{for small errors}$$

$$= \varepsilon_i \, \theta_i,$$

$$\text{where } \theta_i = \partial R/\partial x_i. \qquad (3\text{·}2,7)$$

For propagation of the precision errors

$$S_{result} = \sqrt{\sum_{i=1}^{k} (\theta_i S_i)^2}, \qquad (3\text{·}2,8)$$

and for the bias errors

$$B_{result} = \sqrt{\sum_{i=1}^{k} (\theta_i B_i)^2}. \qquad (3\text{·}2,9)$$

If unsymmetric bias limits exist, then upper and lower B_{result} will need to be calculated separately.

Calculation of the influence coefficients θ_i may use analytic or, more probably, numerical partial differentiation by calculating the change in results ΔR for an incremental change in the element x_i, Δx_i. Then,

$$\theta_i = \frac{\Delta R}{\Delta x_i} \; .$$

For measurements where data reduction is done by computer, this is easily accomplished by adjusting the input value x_i by a small error and allowing the normal data reduction program to produce the new result (i.e., no new

programs are required for this task).

Output for Phase C. The influence coefficients θ_i and the resulting precision and bias indicators provide:

$$S_{result} = \sqrt{\sum_{i=1}^{k}(\theta_i S_i)^2} \qquad (3\text{·}2,10)$$

$$B_{result} = \sqrt{\sum_{i=1}^{k}(\theta_i B_i)^2}$$

3.2.4.4 Phase D - total uncertainty interval for precision errors. The precision index for the final result has been calculated in 3.2.4.3 above, as

$$S_{result} = \sqrt{\sum_{i=1}^{k}(\theta_i S_i)^2} \qquad (3\text{·}2,11)$$

The random uncertainty interval is given by

$$t_{95} S_{result} / \sqrt{M} \quad , \qquad (3\text{·}2,12)$$

where M is the number of times the test is repeated and t_{95} is the Student's t distribution associated with 95 percent probability. If S_{result} is based on reliable S_i values (large ν_i), then t_{95} can be approximated by 2. If relatively few samples (<30) contributed to the individual S_i estimates, then t_{95} may be larger than 2 as a result of the limited degrees of freedom for each estimate. But t_{95} is an overall value requiring an 'average' degree of freedom to be attached to the final result. The average needs to be weighted by the magnitude of the S_i's and their individual degrees of freedom, ν_i. This is done by the Welch-Satterthwaite approximation:

$$\nu_{result} = [\sum S_i^2]^2 / [\sum S_i^4 / \nu_i] \qquad (3\text{·}2,13)$$

The S_i and ν_i values are taken from Phase A.

Output from Phase D. The precision uncertainty interval I_r is such that the result R lies within

$$R \pm t_{95} S_{result} / \sqrt{M} \quad \text{(i.e., } R \pm I_r) \qquad (3\text{·}2,14)$$

where $t_{95} = 2$ for large samples, N (see Phase A),

or t_{95} = Student's t distribution with ν_{result} degrees of freedom.

3.2.4.5 Phase E - total uncertainty interval for bias errors.

Output from Phase E. The bias uncertainty interval is such that the result R_{true} lies within

$$R \pm B_{result} ,$$

or $$R - B^-_{result} < R_{true} < R + B^+_{result} , \qquad (3\text{·}2,15)$$

if unsymmetric bias errors are identified.

The values for B_{result} have been calculated in Phase C.

3.2.4.6 Phase F - total uncertainty : precision and bias. The final uncertainty interval on the result is clearly some combination of S_{result} and B_{result}. Expert opinion, however, remains divided between simple addition of the intervals from Phases D and E and the combination of the two by the root sum square method. Currently the international standard admits either method. For ITTC purposes it is proposed that both values are computed initially. Having pursued the analysis as far as this point, the final calculation is numerically trivial.

Output from Phase F

$U_{ADD} = \pm(B_{result} + I_r)$ and $R - U_{ADD} < R_{true} < R + U_{ADD}$;

and (3·2,16)

$$U_{RSS} = \pm\sqrt{B^2_{result} + I_r^2} ,$$

$R - U_{RSS} < R_{true} < R + U_{RSS}$

(N.B., upper and lower limits should be constructed using B^+ and B^- if these are different.)

3.3 Guidelines for Validation and Verification of CFD

3.3.1 Foreword. Computational Fluid Dynamics (CFD) plays an increasingly important role in predicting hydrodynamic performance of ships and offshore structures. CFD enhances the capabilities of ITTC organizations, and complements and changes the role of experimentation, rather than replacing model tests. The investigator's insight into physical processes can be increased by means of CFD, because one can 'step inside the flow' and study the flow in much greater detail than is usually possible through experimentation. Further, CFD provides excellent possibilities for optimizing designs, particularly when CFD is integrated in a computer-aided design (CAD) process. The value of CFD greatly depends on the level of confidence that one has in the results. The level of confidence is determined by the accumulation of experience and experimental verifications carried out. The time span needed to reach a 'mature capability' and the level of confidence can both be influenced in a positive sense by a structured approach during the development. In this respect, the following aspects are of importance:

In the following flow diagram, the various steps that can be discerned in the development process of CFD are listed together with the sources of error that can be associated with these steps. A distinction is made between validation and verification of CFD, where:

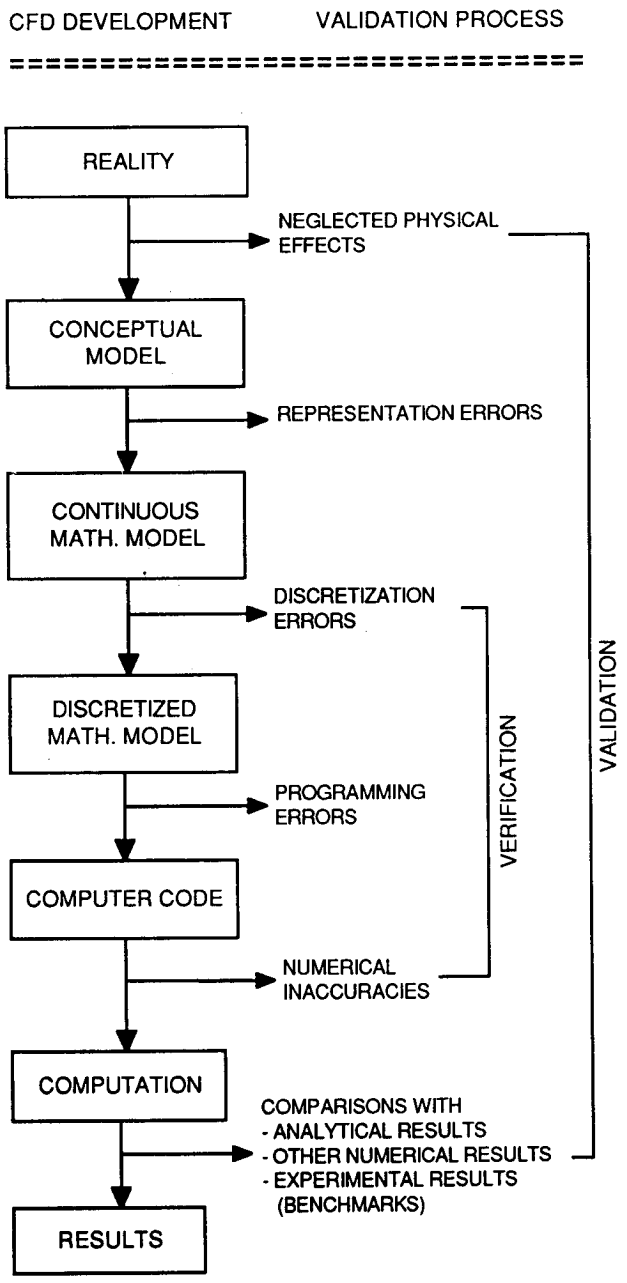
verification of a computer program means to check that the program is actually a correct representation of the mathematical model that forms the basis for it;

validation is the demonstration that the verified computer program is an adequate representation of the physical reality. (Thus, validation is a broader activity which includes verification and comparison with benchmark experimental results.)

Subsequently, the following aspects will be treated:

basic theoretical limitations,
numerical aspects,
software engineering aspects,
verification and validation activities,
documentation.

A Flow Diagram for CFD Development Process



3.3.2 Basic Theoretical Limitations. Each CFD code is based on a mathematical model. It is important for users to be aware of the limitations inherent in the mathematical model underlying the code. Therefore, the basic simplifications must be clearly specified, such as:

linearity;
small amplitude assumptions;
neglected effects: viscosity, shallow water, wall effects, etc.

In many cases, purely theoretical models are supplemented with empirical data (for instance, viscous roll damping, turbulence models), but again it is important to be aware whether or not empirical data is included, and if so, whether the user should specify any empirical input.

3.3.3 Numerical Aspects. A mathematical model is translated into a numerical model, amenable to programming, through discretization. In many cases the accuracy of the numerical processes can be estimated, although this is rarely done in a systematic manner.

Attention should be paid (among other things) to:

modeling and discretization of boundary conditions, limitation of the fluid domain;
grid effects: topography, size of panels (resolution), order of panels;
solution techniques (large matrices);
time and/or space integration: stability, convergence, accuracy, initial conditions (ramping);
numerical accuracy of floating point operations, word length, and single/double precision.

3.3.4 Software Engineering Aspects. Investment in software engineering can enhance the performance of CFD significantly, not only in terms of quality, but also with respect to costs and turnaround. Often, man-hours needed for input preparation are a major part of the total costs. These can be reduced by proper pre- and post-processing routines. Of importance are:

pre-processing (grid generation);
post-processing: data reduction, graphic representation of complex data;
communication with other programs and data bases;
user interfaces;
user guidance systems, expert systems (in this respect it is of importance to state the level of experience that is required for use of a specific program);
software quality assurance (QA).

3.3.5 Verification and Validation Activities. The verification process includes:

comparison with analytical results for special test cases involving simple geometries and limiting values of the parameters;
comparison with benchmark numerical results;
verifications of analytical relations between computed quantities;
verifications by use of relations based on conservation principles involving mass, momentum, and/or energy;
systematic accuracy analysis.

The last item, namely, systematic accuracy analysis, means that numerical error sources are listed and the sensitivity of

final results to each error source is identified. The accuracy analysis can be done by convergence tests where, for instance, grid size or final steps are systematically varied. It is realized that convergence tests are not always possible to do,because of limitations in computer storage and speed. It should be realized that there exists no generally accepted standard procedure for verifying computer programs These are future tasks that have to be dealt with for each specific application. This means one should state what tests are necessary, including specification of structure types, parameter variations and response variables. Section 4 gives two verification examples: a 3D diffraction/radiation program and a strip theory program. Validation of CFD codes requires that the results be compared with results of model tests or full-scale observations. With respect to the development of CFD, model experiments are extremely important. In this respect, the following types of experiment can be discerned:

experiments designed to understand the flow physics;
experiments designed to validate CFD codes, aiming at determining the accuracy and limitations of such codes.

Validation experiments should be carefully designed to provide data in the form and detail required for comparison with numerical results. Also, the accuracy and limitation of the experimental data must be known. Validation should be performed for a range of specified parameters and cases. If possible, the degree of agreement should be specified in quantitative terms, for instance, by using the procedure proposed by Wald (1940).

In the context of this report, a number of items (amongst many others for complete documentation) should be described in the documentation.

3.3.6 Documentation. Confidence in CFD is based on accumulated knowledge and experience. This requires a complete and accessible documentation covering all the aspects discussed in this Section.

3.3.6.1 Object of computation. A differentiation should be made in the level of confidence for the various quantities that can be obtained by the program.

3.3.6.2 Equations and computational conditions. The governing equation(s), auxiliary equation(s) for modeling or closure, and approximations employed should be described together with the boundary conditions.

3.3.6.3 Discretizations and grid/panel generation. The employed method to discretize the governing equations should be described together with its limitations. Examples of the grid scheme or panel arrangements used must be illustrated together with a description of the minimum grid/panel size.

3.3.6.4 Systematic accuracy analyses. The results of the systematic accuracy analyses must be stated when the dependency of grid/panel size or computing domain, convergence, etc. are discussed. Examples for less complicated special cases can be a part of the systematic accuracy analyses when they are compared with the well-accepted computed results or theoretical results.

3.3.6.5 Standard printouts and checks. In order to minimize the possibility of human errors, it is necessary to include several standard printouts and checks.

4. EXAMPLES

A number of examples of application of the guidelines are included in this section. They are not intended to be definitive statements of accuracy for the different methods, but rather illustrations of the use of the techniques. Ideally, they should provoke detailed technical discussion in the appropriate technical circles, challenging and improving the individual assumptions and the completeness of the analysis.

4.1 Resistance Test

4.1.1 Foreword. This is an example of the uncertainty analysis for the resistance test according to "Guidance to Technical Committee of the 19th ITTC on the Application of Procedures to Assess Uncertainty in Measurement and Prediction." The guiding principles for the analysis are as follows:

- The uncertainty, the range for the true value to exist with a certain confidence level, is estimated at each speed.

- Only the data available from the conventional test procedures are used; any special or additional measurements are not required.

- The analysis is extended to the form factor obtained by the Froude method.

Although the data used here are those of a 7m model, the data are not from a single experiment.

4.1.2 Items for Analysis. The following items may be identified as possible error sources:

a) Model geometry and scale effect - model geometric accuracy; scale (blockage, Reynolds number, separation, turbulence stimulation).

b) Flow condition (ambient flow) - turbulence level/ basin oscillation/residual waves; density; viscosity distribution and gradient; and water contamination and temperature non-uniformity.

c) Test condition - alignment and ballasting; carriage speed: accuracy and steadiness/rails; suitable test duration (steadiness of flow); force measurement point; trim and sinkage; and aerodynamic influence of carriage on model.

d) Instrumentation - dynamometer accuracy (resolution and calibration); and data acquisition (sample rate, resolution, etc.).

e) Data analysis - averaging, filtering and fairing.

f) Extrapolation - wetted surface calculation; scaling procedure (Froude method).

The above-listed error sources are categorized into four groups and only those items of Group 4 below will be included for the uncertainty analysis:

- Group 1 - The error sources that can be expected to be removed before the experiments: air bubbles (should be wiped off model before experiments); and temperature (water should be circulated before experiments and the temperature measured often).

- Group 2 - The errors whose uncertainty is hard to be evaluated quantitatively by the traditional experiments or by the filed data: model geometry (manufacturing accuracy, surface roughness, strain and aging of the calculated model displacement); turbulence stimulation; and alignment and ballasting.

- Group 3 - The errors that can be neglected under the ordinary test condition: force measurement point; and aerodynamic influence of carriage on model.

- Group 4 - The errors that should/can be included in the analysis: carriage speed (accuracy and steadiness/rails); steadiness of flow/residual flow and wave; dynamometer accuracy; thermometer accuracy; accuracy of current meter; blockage; data acquisition; data analysis (averaging, filtering, fairing); and Froude method.

* Although the items in Groups 1, 2, and 3 are are not included in the present analysis example, they can be included in a future analysis if desired.

* The experimental conditions and the methods used in eliminating the sources of error listed in Groups 1 and 2 above must be documented explicitly in the report.

* Measurements of the trim and sinkage during the resistance test are recommended and should be reported.

4.1.3 An Example of Analysis

4.1.3.1 Total resistance

- Dynamometer accuracy:

Bias error - The bias error (nonlinearity) is given by the specified accuracy or by a pre-test calibration of the instrument. The nominal accuracy (maximum deviation) of the load cell, used in the present analysis, is 0.2 percent FS (full measuring scale of the instrument), i.e.,

$$B_1 = 0.002 \cdot 7.5\text{kgf} = 0.015\text{kgf}.$$

Precision error - When the calibration curve is given by a linear equation, S_1 is evaluated by

$$S_1 = \sqrt{\sum_{i=1}^{K}(y_i - y_{LS,i})^2/(K-2)} \qquad (4\cdot1,1)$$

where K is number of data used for calibration, y_i is load, and $y_{LS,i}$ is fitted value.

Table 4·1,1 gives the result of calibration, from which we can evaluate S_1,

$$S_1 = 0.005\text{kgf}.$$

- Current meter accuracy (only when the current meter is used):

Bias Error - Fig. 4·1,1 shows the frequency of the deviation from the calibration coefficient of the miniature-propeller type current meter. The data suggest that the accuracy of the current meter is ±0.1 to 0.2 percent. This makes 0.002 m/s difference in speed (=ΔV). The difference in the resistance by ΔV can be estimated by

$$\Delta R = \partial R/\partial V \cdot \Delta V \qquad (4\cdot1,2)$$

where $\partial R/\partial V$ is obtained from the test result. The mean resistance curve shown in Fig. 4·1,2 gives $\partial R/\partial V$ = 3.95 kgf / m/s. Thus,

$$B_2 = 3.95\ \text{kgf/m/s} \cdot 0.002\ \text{m/s} = 0.008\ \text{kgf}.$$

TABLE 4·1,1
Dynamometer Calibration and Its Curve-Fitted Data

NO. i	INPUT: y_k (kgf)	OUTPUT (VOLT.)	$y_i - y_{LS,i}$ (% F.S)
1	0.000	-0.001	0.01
2	3.000	2.001	-0.07
3	6.000	4.012	-0.03
4	9.000	6.022	-0.01
5	12.000	8.031	0.01
6	15.000	10.039	0.02
7	12.000	8.031	0.01
8	9.000	6.025	0.02
9	6.000	4.019	0.04
10	3.000	2.009	0.01
11	0.000	0.003	0.00
12	-3.000	-2.004	0.03
13	-6.000	-4.010	0.04
14	-9.000	-6.015	0.06
15	-12.000	-8.026	0.03
16	-15.000	-10.034	0.02
17	-12.000	-8.030	-0.01
18	-9.000	-6.026	-0.05
19	-6.000	-4.019	-0.05
20	-3.000	-2.009	-0.02
21	0.000	-0.002	0.00

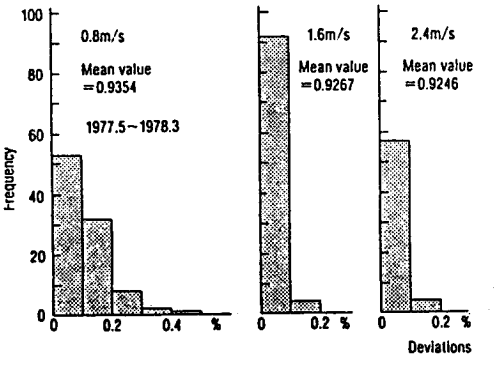


Fig. 4·1,1 Frequency Histogram of Current Meter Deviation

TABLE 4·1,2
Carriage Speed and Relative Speed

EXP. NO.	CARRIAGE SPEED VC(m/S)	RELATIVE SPEED VM(m/S)	|VM-VC|/VC
1	0.500	0.504	0.008
2	0.500	0.506	0.012
3	0.600	0.610	0.017
4	0.700	0.711	0.016
5	0.820	0.831	0.013
6	0.900	0.911	0.012
7	1.000	1.012	0.012
8	1.100	1.110	0.009
9	1.200	1.210	0.008
10	1.300	1.309	0.007
14	1.400	1.404	0.003
11	1.400	1.410	0.007
12	1.500	1.508	0.005
13	1.600	1.606	0.004

TABLE 4·1,3
Numerical Accuracy of Thermometer

	LEVEL	NOMINAL ACCURACY
THERMOMETER	0.3	±0.3 °C
	0.5	±0.5 °C
	1.0	±1.0 °C
	1.5	±1.5 °C

TABLE 4·1,4
Density and Viscosity Coefficient

℃	ρ (kgf• sec²/m⁴)	ν x 10⁶ (m²/sec)
0	101•96	1•792 1
5	101•97	1•518 8
10	101•94	1•308 0
15	101•88	1•141 3
20	101•79	1•006 7
25	101•67	0•896 17
30	101•52	0•804 24
40	101•18	0•659
50	100•76	0•556
60	100•26	0•478
70	99•71	0•416
80	99•10	0•367
90	98•44	0•328
100	97•73	0•296

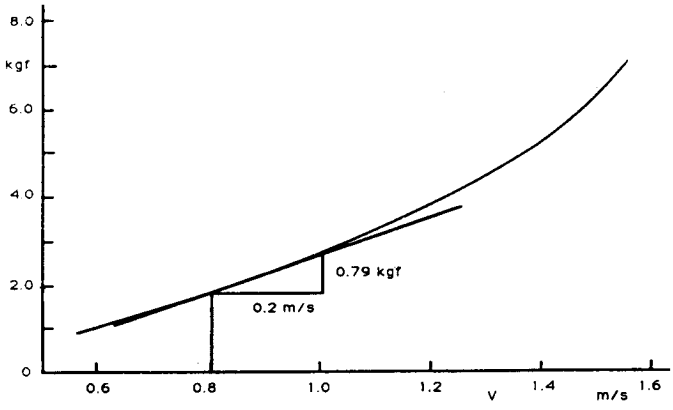


Fig. 4·1,2 Resistance Data

- Residual flow:

Bias error - Table 4·1,2 shows the difference between the carriage speed and the relative speed (measured by a current meter). The difference is ±1 percent on the average that amounts to 0.008 m/s error at Fn = 0.1. This difference in the speed leads to an error in the resistance of

$$B_3 = 0.032 \text{ kgf.}$$

Clearly, if the relative speed is used in the analysis, B_3 should be zero.

- Blockage effect:

Bias error - The speed increment due to the blockage effect is estimated by

$$\Delta V/V = 0.67 \cdot m \cdot (L/B)^{3/4} \cdot (1\text{-}Fh^2)^{-1} \qquad (4\text{·}1,3)$$

where $m=A_m/A_T$ (A_m and A_T are the section areas of the model and tank, respectively); L is model length; b is the tank width; $F_h=V/\sqrt{gh_T}$; h_T is the tank depth (Tamura's formula).

In the present case m=0.0047 and ΔV is 0.001 m/s; therefore,

$$B_4 = 3.95 \text{ kgf/m/s} \cdot 0.001 \text{ m/s} = 0.004\text{kgf.}$$

Precision error - Equation (4·1,3) itself may have a precision error in its assumption. If it is assumed to be 10 percent of the corrective resistance 0.004 kgf, then

$$S_4 = 0.0001\text{kgf.}$$

- Thermometer accuracy:

Bias error - Table 4·1,3 shows the nominal accuracy of the thermometer by JIS (Japanese Industrial Standard). Thermometers of level 0.3 or 0.5 are commonly used in the tank test. The bias error is assumed to be 0.5 percent.

Table 4·1,4 lists the density and the viscosity coefficients of fresh water. $\partial\rho/\partial T$ is ±0.015 at 15° C, while $\partial C_f/\partial T$ is ±0.42 percent C_f at Rn=10E+6 as shown in Table 4·1,5, where T is temperature. These errors do not appear explicitly in the absolute values of resistance but can creep into the resistance coefficients and the form factor analyses.

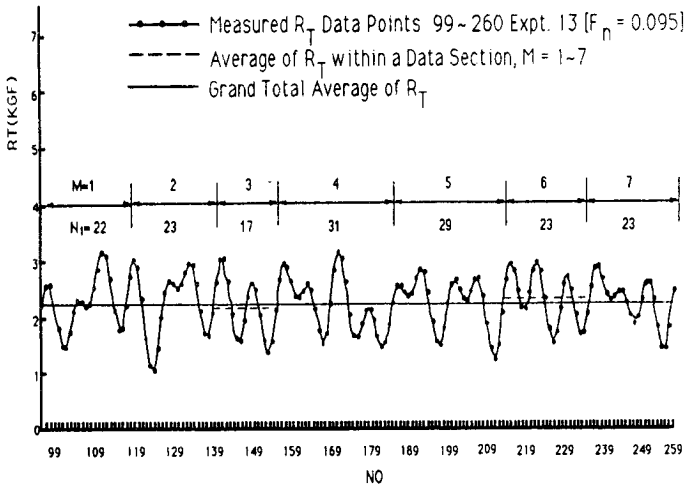


Fig. 4·1,3 Record of Resistance Data

TABLE 4·1,5
Temperature Dependency of C_F

15°C		16°C			
R_n	C_F	R_n	C_F	dC_F	
4.397E+5	5.192E-3	4.513E+5	5.164E-3	0.0277E-3	0.53%
8.794E+5	4.520E-3	9.026E+5	4.498E-3	0.0228E-3	0.50%
1.319E+6	4.183E-3	1.354E+6	4.162E-3	0.0205E-3	0.49%
1.759E+6	3.965E-3	1.805E+6	3.946E-3	0.0190E-3	0.48%
2.199E+6	3.806E-3	2.257E+6	3.788E-3	0.0179E-3	0.47%
3.298E+6	3.540E-3	3.385E+6	3.524E-3	0.0162E-3	0.46%
4.397E+6	3.367E-3	4.513E+6	3.352E-3	0.0151E-3	0.45%
5.496E+6	3.241E-3	5.642E+6	3.227E-3	0.0143E-3	0.44%
6.596E+6	3.143E-3	6.770E+6	3.129E-3	0.0137E-3	0.44%
7.695E+6	3.063E-3	7.898E+6	3.050E-3	0.0132E-3	0.43%
8.794E+6	2.997E-3	9.026E+6	2.984E-3	0.0128E-3	0.43%
9.894E+6	2.939E-3	1.015E+7	2.927E-3	0.0124E-3	0.42%
1.099E+7	2.890E-3	1.128E+7	2.877E-3	0.0121E-3	0.42%
1.209E+7	2.845E-3	1.241E+7	2.834E-3	0.0119E-3	0.42%

TABLE 4·1,6
Ensemble Average of Measured Resistance Within Data Section

i	N_i	$\bar{R}_i$ (kgf)
1	22	2.2395
2	23	2.2592
3	17	2.1615
4	31	2.2176
5	29	2.2295
6	23	2.2946
7	23	2.2404

- The resolution of data recorder:

Bias error - When the recorded information is converted into digital data, the resolution is given by

$$FS(kgf)/ND \qquad (4\cdot1,4)$$

where FS is the full scale of the dynamometer and ND is the maximum digit. In case ND=4000 for FS=15kgf, we have

$$B_6 = 15kgf/4000 = 0.004kgf.$$

- Data analysis:

Bias error - Fig. 4·1,3 is a typical example of recorded data. If it represents fluctuations due to model surge, then the possibility of a bias error in the measured resistance must be considered. The bias (i.e., offset) would result from the non-linear relation between relative velocity and resistance.

Precision error - Because repeated measurements are usually not carried out in the resistance test, we split N (in this example 168) recorded data into M (=7) data sections. Each of these sections must cover at least two or three cycles of fluctuations and can be considered as independent measurements (M>2). Table 4·1,6 shows the average of each group. The precision index is calculated by

$$S_7 = \sqrt{\sum_{i=1}^{M}(R_i - \bar{R})^2/(M-1)} \qquad (4\cdot1,5)$$

where R_i is the average of the i-th data section, while $\bar{R}$ is the grand average. In the present example, $\bar{R}$ is 2.243kgf and S_7 = 0.004kgf.

This index is 0.18 percent of the grand average. Now, the final results are as follows:

In case of using the relative speed:

$$S_{result} = \sqrt{S_1^2 + S_4^2 + S_7^2} = 0.006 \text{ kgf},$$

$$B_{result} = \sqrt{B_1^2 + B_2^2 + B_4^2 + B_6^2} = 0.018 \text{ kgf},$$

$$U_{ADD} = B_{result} + t_{95}S_{result} = 0.030 \text{ kgf} \quad (1.34\% \text{ of } \bar{R}),$$

$$U_{RSS} = \sqrt{B_{result}^2 + (t_{95}S_{result})^2} = 0.18\text{kgf} \quad (0.80\% \text{ of R}),$$

where t_{95} is the Student's t distribution for which 2.0 can be used for this case.

$$R = \bar{R} \pm U_{ADD} = 2.243\,kgf \pm 0.030kgf .$$

In case of using the carriage speed:

$$S_{result} = \sqrt{S_1^2 + S_4^2 + S_7^2} = 0.006 \text{ kgf},$$

$$B_{result} = \sqrt{B_1^2 + B_3^2 + B_4^2 + B_6^2} = 0.036 \text{ kgf},$$

$$U_{ADD} = 0.048 \text{kgf},$$

$$U_{RSS} = 0.038 \text{kgf},$$

$$R = \bar{R} \pm U_{ADD} = 2.243 \text{ kgf} \pm 0.048 \text{ kgf} .$$

4.1.3.2 Resistance coefficient

$$C_t = \bar{R} / \tfrac{1}{2}\rho V^2 S \pm C_t \cdot (U_{ADD}/\bar{R} - \Delta\rho/\rho - 2\Delta V/V)$$
$$= 4.166 \cdot 10^{-3} \pm 4.166 \cdot 10^{-3} \cdot (0.030/2.243 \ (4\text{·}1,6) \ -0.015/101.88 \cdot 0.5 - 2 \cdot 0.002/0.8220)$$
$$= (4.182 \pm 0.037) \cdot 10^{-3} .$$

Here, the error of the wetted surface area is neglected.

4.1.3.3 Form factor

Error Sources: the error in C_t at the Fn around which the form factor k is determined; the error in C_f due to the temperature error; and the error in the determination of the form factor k itself.

- The error in C_t: Δk_1

$$C_t \pm \Delta C_t = C_f(1+k\pm\Delta k_1) + C_w , \text{ and}$$

$$\Delta k_1 = \Delta C_t / C_f . \qquad (4\text{·}1,7)$$

Here $C_t = 0.037 \cdot 10^{-3}$ and $C_f = 3.157 \cdot 10^{-3}$, then $\Delta k_1 = 0.012$.

- The error in C_f due to the temperature error: k_2

$$C_t = (C_f \pm \Delta C_f)(1+k\pm\Delta k_2) + C_w , \text{ and}$$

$$\Delta k_2 = \Delta C_f(1+k)/C_f . \qquad (4\text{·}1,8)$$

Here $C_f = 3.157 \cdot 10^{-3}$, $\Delta C_f = 0.042 \cdot 3.157 \cdot 10^{-3} \cdot 0.5 = 0.066 \cdot 10^{-3}$ and $k = 0.33$,

then $\Delta k_2 = 0.003$.

- The error in the determination of k: k_3

The maximum resolution of k in the conventional method can be assumed to be 0.01, then

$$\Delta k_3 = 0.005 .$$

Now the total error is

$$\Delta k_{total} = \sqrt{\Delta k_1^2 + \Delta k_2^2 + \Delta k_3^2}$$
$$= \sqrt{(0.012)^2 + (0.003)^2 + (0.005)^2}$$
$$= 0.013,$$

$$k = 0.33 \pm 0.01 .$$

4.1.4 Discussions. The above uncertainty analysis depends on the assumptions explained in the text:

Are the sources correct?
Are the error estimates reasonable?
Is the bias B_7 important?
How do the answers compare with expectation?

This is intended just as an example of how to use the methodology, NOT as a definitive statement on the uncertainty analysis of a resistance test. The example reported here is the result of a cooperative effort by the Panel and the following contributors: Mr. Kasahara (NKK), Dr. Kusaka (Mitsui Akishima RI), Dr. Ogiwara (IHI), and Dr. Yamaguchi (SRI). The Panel is pleased to acknowledge their contributions.

4.2 Error Analysis and Validation in Maneuvering Studies

4.2.1 Foreword. Many present-day maneuverability studies are devoted to predicting what a ship or other marine vehicle will do in a dynamic sense when a type of control action occurs. Predictions may be based on the results of physical or mathematical models, but in all cases it is essential to know how reliable and accurate is the prediction. When assessing the validity of these predictions, it is imperative that due account be taken of the accuracy, not only of the baseline data, but also of the prediction method. This involves an estimation of the errors inherent in the process under consideration and ultimately a judgment of what is an acceptable level of error for a particular purpose. As an example, simulation results used to train mariners can be acceptable even if the predicted ship position at any instant is relatively inaccurate. However, the same level of error would be unacceptable if the simulation were to be used to predict a ship's position for the purpose of accurate navigation under a narrow bridge or to determine the amount of material to be blasted out of rock to make a canal. The following is an attempt to identify possible sources of precision and bias errors in physical and mathematical models associated with maneuvering studies.

4.2.2 Sources of Error

4.2.2.1 Physical model tests. Physical model tests under laboratory conditions provide the best means to minimize error by proper control of the experiment conditions. In the following, we assume that obvious sources of gross error, such as faulty equipment or incorrect analysis procedures, have been eliminated. What remains are the bias and precision errors that are either difficult or impossible to remove under normal conditions, or that can simply be neglected.

Precision errors may occur in the following items where, for the moment, no measure of importance is assigned to each item:

model geometric accuracy;
control surface positioning accuracy;
model speed measurement;
accuracy of drift, heading, incidence and roll angle measurement;
model position;
model ballasting and dynamic balancing;
general instrumentation errors.

Bias errors:

scale effects;
steady tank currents;
wind resistance of the model;
instrumentation errors;
tank blockage.

4.2.2.2 Full-scale experiments. In full scale the investigators inevitably have less control over all conditions of the experiment compared to the 'laboratory' conditions of the towing tank or model basin. Proper assessment of all sources of error is therefore essential on full-scale measurements because these are invariably taken as providing the ultimate validation data for physical or numerical model predictions. Full-scale maneuvering experiments are comparatively rare (if we here make the distinction between maneuvering experiments, such as those on the 'Esso Bernicia' and the 'Esso Osaka,' and builder's maneuvering trials) and therefore methods of conducting them are by no means 'standard.' If we also include System Identification techniques, we see that the proper determination of errors is difficult and complex. However, in order to make a start, the following sources of error, including both builder's trials and maneuvering 'experiments,' are offered as a basis for discussion.

- Precision errors:

  control surface positioning accuracy;
  ship speed;
  heading and ship motions;
  environmental measurements;
  ship position;
  general instrumentation errors.

- Bias errors:

  hull condition;
  rudder and other control surface positions;
  environmental conditions;
  position fixes;
  water depth;
  general instrumentation errors.

4.2.2.3 Mathematical modeling: analysis. By mathematical modeling, we are mainly considering maneuvering simulation, but these general remarks apply also to the analysis procedures adopted with model- and full-scale experimental data.

The notes below are intended to provide a stimulus for discussion. They are by no means comprehensive, but hopefully address some of the main sources of error. Probably the best approach to error analysis in simulation models is to carry out a comprehensive sensitivity analysis by varying coefficients in the whole model in a systematic manner and judging their effect on the results. The sensitivity of the model to the accuracy of the coefficients themselves (which should be calculable, as most depend on physical measurements) can then be determined. However, it is perhaps appropriate to consider some sources of error:

round-off noise;
curve fitting;
numerical techniques;
linearization and simplification;
discretization.

4.2.3 An Example of Error Estimation. An ideal source for maneuvering error estimation would be the model, numerical and full-size measurements of the 'Esso Osaka.' Once these are all complete then perhaps a useful exercise for ITTC would be an attempt to identify and quantify sources of error. This is especially relevant to the full-scale measurements. However, in the absence of such a detailed analysis the following is offered as an example. It relates to a model test carried out in shallow water where the model's tracks along a buoyed channel had to be measured. Marker buoys had been set in the basin at pre-determined positions and the absolute model position, relative to the marker buoys, was of some importance in the investigation. The purpose of the error analysis was therefore to determine the probable accuracy of the measured track of the model.

4.2.3.1 Sources of error. The sources of error were as described in Section 4.2.2 and will not be repeated here. However, it may be noted that track speeds were not measured directly, but deduced from the first derivative, with time, of the track measurements.

4.2.3.2 Error estimates. The standard precision errors of various key measurements were first estimated. This was based on either past experience or a knowledge of the capabilities of the instrumentation involved. Bias errors were, in this instance, assumed to be negligible.

- Rudder angle - The standard error of the measured rudder angle, δ, was estimated to be $\pm 1.0°$.

- Heading - The standard error of the measured heading was estimated to be $\pm 1.0°$.

- Shaft rpm - The standard error of the measured shaft rpm, N, was estimated to be ± 1.0 rpm.

- Time - Timing was derived from very accurate instrumentation. Timing errors were therefore assumed to be negligible.

- Marker buoys - The marker buoys were estimated to have a relative positional accuracy of ± 5mm (i.e. the channel widths were accurate to this value) and an absolute positional accuracy within the basin of ± 15mm. The buoys delineated the nominal channel boundary given on a chart which itself was presumably subject to (unknown) error. (Further errors due to scaling from the drawing probably resulted in an overall error of ± 1.0 m in the channel boundary definition.) Therefore, although the marker buoys delineated a channel, these buoys were regarded as the 'best' representation of the particular channel in question.

- Track - To illustrate the potential error of the derived (x,y) coordinates of the model position within the tank, the position was assumed to be deduced from signals obtained

from two receivers at positions 1 and 2 in Figure 4·2,1. Thus, there are two measurements of the length of the rays R1 and R2 from the transmitter in the model to receivers 1 and 2 (see Figure 4·2,2). Checks on the measurement of known distances in the tank suggested that the rays would be measured to ±0.015 m while the base length L was measured to an accuracy of ±0.005 m. Using these values for a position between two channel marker buoys gave values of R_1 and R_2 of 32 m and 28 m , respectively. Using the cosine rule to give cosα we have:

$$\cos\alpha = (R_1^2 + L^2 - R_2^2)/(2R_1L) \qquad (4\cdot2,1)$$

The (x,y) coordinates may be calculated from

$$x = R_1 \cos\alpha, \qquad (4\cdot2,2)$$

$$y = R_1 \sin\alpha. \qquad (4\cdot2,3)$$

The error in the derived value of cosα was obtained from

$$\varepsilon^2\cos = \frac{(\partial f)^2}{(\partial R_1)}\,\varepsilon_{R_1}{}^2 + \frac{(\partial f)^2}{(\partial R_2)}\,\varepsilon_{R_2}{}^2 + \frac{(\partial f)^2}{(\partial L)}\,\varepsilon_{l}{}^2 \qquad (4\cdot2,4)$$

where εβ denotes the estimated error of a quantity β and f denotes the expression on the right hand side of Equation (4·2,1).

Similarly

$$\varepsilon_x{}^2 = \frac{(\partial g)^2}{(\partial R_1)^2}\,\varepsilon_{R_1}{}^2 + \frac{(\partial g)^2}{(\partial(\cos\alpha))^2}\,\varepsilon_{\cos\alpha}{}^2 , \qquad (4\cdot2,5)$$

$$\varepsilon_y{}^2 = \frac{(\partial h)^2}{(\partial R_1)^2}\,\varepsilon_{R_1}{}^2 + \frac{(\partial h)^2}{(\partial(\sin\alpha))^2}\,\varepsilon_{\sin\alpha}{}^2 , \qquad (4\cdot2,6)$$

where g and h are the functions on the right hand sides of Equations (4·2,2) and (4·2,3).

Using values obtained for a position between the marker buoys in question gives the following percentage errors:

$$\varepsilon_{\cos\alpha} = \pm 0.00117\%,$$
$$\varepsilon_x = \pm 0.051\%,$$
$$\varepsilon_y = \pm 0.051\%.$$

These results indicate that the x and y position coordinates have an absolute error of ±12mm at model scale for the position chosen. In practice, results for each position were obtained from all four receivers and a 'best fit' (in the least squares sense) result obtained for x and y. It was therefore assumed that the model (x,y) positions had an error of ±12 mm as an upper bound. This represented a positional error of ±0.48 m at full scale.

- Track Speed. Track speed was derived from

$$v_t = \delta s/\delta t \qquad (4\cdot2,7)$$

where δs is the distance along track from position 1 to

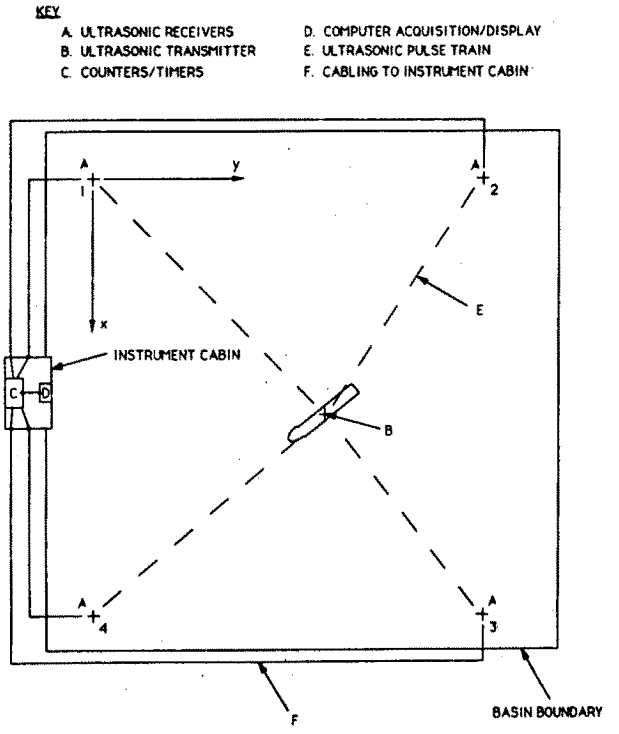


Fig. 4·2,1 BMT Ultrasonic Tracking System

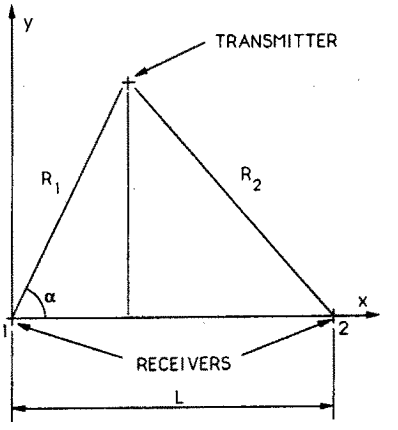


Fig. 4·2,2 Definition Sketch for Error Analysis

position 2 moved in time δt and is given by

$$\delta s = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \ . \qquad (4\cdot2,8)$$

Thus we have

$$\varepsilon v_t{}^2 = \left[\frac{(\partial v_t)}{\partial(\delta s)}\right]^2 \varepsilon^2{}_{\delta s} + \left[\frac{(\partial v_t)}{\partial(\delta t)}\right]^2 \varepsilon^2{}_{\delta t} \qquad (4\cdot2,9)$$

which, because we have assumed $\varepsilon_{\delta t}$ to be zero, becomes

$$\varepsilon v_t = \frac{\partial v_t}{\partial(\delta s)}\,\varepsilon_{\delta s} = \varepsilon\frac{\delta s}{\delta t} \ . \qquad (4\cdot2,10)$$

Now the precision error in δs is given by

$$\varepsilon_{\delta s}^2 = \left[\frac{\partial(\delta s)}{\partial x_1}\right]^2 \varepsilon_{x_1}^2 + \left[\frac{\partial(\delta s)}{\partial x_2}\right]^2 \varepsilon_{x_2}^2 + \left[\frac{\partial(\delta s)}{\partial y_1}\right]^2 \varepsilon_{y_1}^2 + \left[\frac{\partial(\delta s)}{\partial y_2}\right]^2 \varepsilon_{y_2}^2 . \quad (4\cdot2,11)$$

Taking typical values of x_1, x_2, etc. at the same two marker buoys and values of ε_x and ε_y, as given above, we obtain,

$$\varepsilon_{\delta s} = \pm 0.072\%,$$

so that, with a 1.0 second timing interval,

$$\varepsilon_{v_t} = \pm 0.072\%.$$

Thus the error in speed while small, is some 40 percent greater than the error in position measurement.

4.2.4 Concluding Remarks. This contribution has been provided by members of the Maneuvering Committee. It has been an attempt to apply the initial thoughts of the Panel on Validation Procedures to the particular case of maneuvering. Special recognition is due to Dr. I. W. Dand for his efforts.

4.3 Speed and Power Trials

4.3.1 An Uncertainty Analysis for Speed and Power Trials. Ship delivery trials are carried out to establish the relationship between ship speed (through the water), shaft power and propeller revolutions under specific loading conditions. It is necessary to take into account that ship trials are usually carried out not for scientific purposes, but to fulfill contract obligations between builders and owners relating to speed, engine power, and fuel consumption. Thus, the accuracy achievable is dependent on a reasonable allocation of funds and resources. The results of trials would refer to some environmental conditions normally referred to as the no-wind, calm sea, no-current, deep water performances of the ship.

According to Denny (1951), the measurements may be divided into the following areas:

Ship State Measurements.
Ship Performance Measurements.
Environmental Measurements.
Analysis Method.

The last item 'Analysis Method,' though not a part of the measurements, should be included in an uncertainty analysis.

4.3.2 Items for Analysis

4.3.2.1 Ship state measurement. Ship state measurements relate to the condition of the ship and, in terms of speed/power trials, include:

ship displacement,
ship trim,
ship heel,
ship roughness,
propeller geometry (diameter, pitch, ...),
propeller roughness.

4.3.2.2 Ship performance. This set of measurements relates to the performance of the ship and includes:

ship speed,
shaft torque,
shaft thrust,
shaft revolutions,
rudder angle,
heading and yaw angle,
ship motions.

4.3.2.3 Environment. Following are the environmental conditions affecting speed trials that usually need to be accounted for:

wind speed and direction,
sea conditions,
sea temperatures,
current,
water depth.

4.3.2.4 Analysis method. The procedure for analyzing the speed trial data involves reducing the data to the standard conditions of no-wind, calm sea and deep water. Thus, procedures are developed to provide corrections for the following factors:

wind effects,
rudder-added resistance due to rudder movements,
added resistance due to waves,
sea temperature,
tidal and current effects,
speed losses due to shallow water.

For an uncertainty analysis, the accuracy of the above correction procedures must be assessed. However, as the weather becomes severe, the accuracy assessment for the correction procedures becomes less certain, and the reliability of the corrected trial results becomes dependent on the accuracy of the correction procedures.

4.3.3 An Example From Sea Trials. In this paragraph, attention is devoted to the area of Ship Performance Measurements with particular reference to shaft torque and shaft revolutions.

4.3.3.1 Error evaluation applied to indirect and non-repeated measurements. In the indirect measurements the physical quantity to be examined is a function of several physical parameters:

$$Y = F(U,V,...).$$

Therefore, the Y measurement is carried out after the direct measurements u, v, etc. of U,V, etc, have been performed. Thus,

$$y = f(u,v,...).$$

The maximum absolute error $\underline{\Delta}y$ of y will be a function of the single absolute errors $\underline{\Delta}u$, $\underline{\Delta}v$, etc. of the quantity U, V, etc. Assuming that the error terms $\underline{\Delta}u$, $\underline{\Delta}v$, etc. are so small that the powers greater than the first power, as well as the cross-products like $\underline{\Delta}u \cdot \underline{\Delta}v$, ...etc., are negligible, the maximum absolute error $\underline{\Delta}y$ may be given by:

$$(\underline{\Delta}y)^2 = (|\partial f/\partial U| \cdot \underline{\Delta}u)^2 + (|\partial f/\partial V| \cdot \underline{\Delta}v)^2 + ...,$$

where partial derivatives must be calculated at the point P(u,v,...). The maximum relative error is then defined by the following expression:

$$(\Delta y/y)^2 = (|\partial f/\partial U| \cdot \underline{\Delta}u/y)^2 + (|\partial f/\partial V| \cdot \underline{\Delta}v/y)^2 + ...$$

4.3.3.2 Powering tests. The power measurements usually are performed by reading the torque and rpm on the shafting line. The revolutions are measured by an instrument secured near the shaft to pick up signals from N metal bars equally spaced around the circumference of the shaft. The speed of the shaft is thus given by the number of impulses per minute divided by the number of bars N.

The torque on the shaft is measured by strain gauges. A four-branch extensometer bridge is applied directly to the shaft and measures the deformation produced by the torsion load. The voltage variations output by the bridge due to the extensometer resistance changes modulate the frequency of an oscillator mounted on the shaft, which in turn feeds the extensometer bridge. The frequency signal is sent to a display through two coils, one movable along the shaft and one fixed. In order to correlate the frequency value read on the instrument to the actual torsional strain, the instruments are calibrated first in a laboratory and then on board ship (Table 4·3,1) on the basis of rated acting loads and of the electrical characteristics of the circuit.

The power P will thus be given by:

$$P = C_t \cdot \underline{\Delta}F \cdot N/716.2 \qquad [cv] \ . \qquad (4\cdot3,1)$$

The meaning of the individual terms and their units of measurement are shown in Table 4·3,1. This table refers to a sample vessel of a common type.

Power measurement is thus an indirect measurement. In order to assess error it is necessary to represent expression (4·3,1) as a function of the single terms directly measurable. Simple passages thus lead to:

$$P = G \cdot \pi/32 \cdot D^3 \cdot R/K(R+Rc) \cdot \underline{\Delta}F/\underline{\Delta}Fc \cdot N/716.2 \ . \qquad (4\cdot3,2)$$

In order to evaluate the maximum absolute and maximum relative error made in measuring the power, the relative error theory is applied to 'Indirect' and 'Nonrepeated' measurements. The maximum absolute error $\underline{\Delta}P$ will be a function of the single absolute errors $\underline{\Delta}G$, $\underline{\Delta}D$, $\underline{\Delta}R$, $\underline{\Delta}K$, $\underline{\Delta}Rc$, $\underline{\Delta}(\underline{\Delta}F)$, $\underline{\Delta}(\underline{\Delta}Fc)$ and $\underline{\Delta}N$.

- Bias errors: The error made in evaluating the torsional elasticity modulus 'G' is a 'Bias' error. This error may be small if the shaft, on which the extensometer is mounted, has been calibrated beforehand in a laboratory (as is normally the case for naval vessels). Otherwise, shaft calibration is not possible. Therefore a mean value of G is usually chosen by statistical means based on all the shafting line calibrations carried out by individual institutions. Table 4·3,2 and Figure 4·3,1 show a histogram of 46 values of G obtained from the CETENA data bank. The mean value of G (its most probable value) and the standard deviation (maximum absolute error) are shown in Table 4·3,3.

- Precision errors: Errors $\underline{\Delta}D$, $\underline{\Delta}R$, $\underline{\Delta}K$, $\underline{\Delta}Rc$, $\underline{\Delta}(\underline{\Delta}F)$, $\underline{\Delta}(\underline{\Delta}Fc)$ and $\underline{\Delta}N$ are 'precision' errors, and are calculated as follows:

a) The maximum absolute error $\underline{\Delta}D$ is a function of the reading constant of the instrument used to measure the shaft diameter. A common practice is to measure the shaft circumference with a graduated unstretchable wire that has a reading constant of 0.0005m. We have therefore:

$$\Delta D = \pm 0.0005/\pi \qquad [m] \ .$$

b) The maximum absolute errors $\underline{\Delta}R$, $\underline{\Delta}K$, and $\underline{\Delta}Rc$ depend on the type of resistance used, and have already been calculated by the manufacturers. The extensometers used have the following values:

$$\underline{\Delta}R = \pm 1.40 \ [\Omega],$$
$$\underline{\Delta}K = \pm 0.0102,$$
$$\underline{\Delta}Rc = \pm 130 \ [\Omega].$$

c) The maximum absolute error $\underline{\Delta}(\underline{\Delta}Fc)$ is minimal ($=10^{-6}$ Hz), as it is linked to the frequency-meter reading constant, and may therefore be neglected.

d) The absolute maximum error $\underline{\Delta}(\underline{\Delta}F)$ is a different matter. In measuring ΔF, in addition to the (negligible) error related to the reading constant of the instrument, errors due to the following sources must also be considered: temperature variations during testing; voltage variations during testing; and imperfect linearity of the oscillator. These errors have been assessed by laboratory tests in which several oscillators have been subjected to different load conditions. The results of these tests have yielded the following mean maximum relative errors:

temperature : ±0.15%/10°C in the 20°C ~ 70°C range;
voltage : ±0.5%/Volt;
linearity : ±0.5%.

If we assume that in most cases the temperature variations during the test do not exceed 10°C, and that voltage variations do not exceed 0.3 Volts, we may estimate the $\underline{\Delta}(\underline{\Delta}F)$ for the vessel presented in Table 4·3,1 as:

$$\underline{\Delta}(\underline{\Delta}F) = 13 \ [Hz].$$

e) The maximum absolute error $\underline{\Delta}N$ depends on the number of bars installed around the shaft. Generally speaking, between 4 and 8 bars are used, giving:

$$\underline{\Delta}N = 1/6 \ [rpm].$$

Based on the above, we may assess the maximum absolute error $\underline{\Delta}P$:

$$\Delta P = \Delta P' \pm \Delta G$$

$$\Delta P' = |\partial P/\partial D| \cdot \Delta D + |\partial P/\partial R| \cdot \Delta R + |\partial P/\partial K| \cdot \Delta K + |\partial P/\partial Rc| \cdot \Delta Rc + |\partial P/\partial(\Delta F)| \cdot \Delta(\Delta F) + |\partial P/\partial(\Delta Fc)| \cdot \Delta(\Delta Fc) + |\partial P/\partial N| \cdot \Delta N.$$

- Maximum relative error in power measurements: Applying this theory to the sample vessel, we may evaluate the percentage relative error contribution of the single terms (Table 4·3,4) to the maximum relative error $\Delta P/P$. According to the literature on this subject, the precision error can be evaluated through the following formula:

$$\frac{\Delta P'}{P} = \sqrt{\sum_i \left(\frac{\partial P'}{\partial x_i} \cdot \frac{\Delta x_i}{P} \right)^2}$$

$$= \sqrt{\sum_i (\theta_i \cdot S_i)^2}.$$

Using this formula for the values of $\theta_i \cdot S_i$ given in Table 4·3,4, the following results will be obtained for the precision error:

$$\frac{\Delta P'}{P} = \pm 1.09\%.$$

The total error (bias plus precision) is then given by

$$\frac{\Delta P}{P} = \pm \sqrt{\left(\frac{\Delta P}{P}\right)^2 + \left(\frac{\Delta G}{P}\right)^2}$$

$$= \pm 1.55\%.$$

Table 4·3,1

Starting data			
Power rating	P	$6.355 \cdot 10^6$	[W]
Related rpm	N	127	[rpm]
Shaft diameter	D	0.372	[m]
Shear modulus	G	$79.695 \cdot 10^9$	[N/m²]
Strain gages data			
Resistance	R	350	[Ω]
Gage factor	K	2.045	
Resulting data			
Rated torque	Q=P/N	$477.841 \cdot 10^3$	[N · m]
Polar moment of inertia	$J=\pi \cdot D^4/32$	$1.88 \cdot 10^{-3}$	[m⁴]
Shaft constant	$C_s=4 \cdot G \cdot J/D$	$1.611 \cdot 10^9$	[N · m]
Strain	$\varepsilon=Q/Cs$	$296.611 \cdot 10^{-6}$	
Calibration data			
Resistance	$R_c \leq R/(4 \cdot K \cdot \varepsilon)$	144.254	[KΩ]
Resistance of calibration	R_c	140.000	[KΩ]
Related strain	$\varepsilon_c=R/(4 \cdot K \cdot (R+R_c))$	$304.861 \cdot 10^{-6}$	
Calibration frequency			
(positive difference)	Δf^+	1800	[Hz]
(negative constant)	Δf^-	1800	[Hz]
Constants			
Positive constant	$C_t^+=C_s \cdot \varepsilon_c/\Delta f^+$	272.851	[N · m/Hz]
Negative constant	$C_t^-=C_s \cdot \varepsilon_c/\Delta f^-$	272.851	[N · m/Hz]

Table 4·3,2
Shear Modulus Values [N/mm²]

(1)	79951.5	(17)	79078.4	(32)	78009.1
(2)	81423	(18)	80324.3	(33)	79657.2
(3)	79725.9	(19)	78725.3	(34)	80912.9
(4)	81923.3	(20)	79058.8	(35)	80049.6
(5)	81423	(21)	78852.8	(36)	80020.2
(6)	81423	(22)	80530.3	(37)	80265.4
(7)	79029.4	(23)	78607.5	(38)	78077.8
(8)	79784.7	(24)	79117.7	(39)	80157.5
(9)	79156.9	(25)	79784.7	(40)	80128.1
(10)	78911.6	(26)	79029.4	(41)	79843.6
(11)	78077.8	(27)	79853.4	(42)	79961.3
(12)	80334.1	(28)	81128.7	(43)	79245.2
(13)	80039.8	(29)	78480	(44)	79971.1
(14)	80186.9	(30)	78578.1	(45)	79196.1
(15)	79774.9	(31)	79137.3	(46)	79421.8
(16)	79588.5				

Table 4·3,3
Summary Statistics

Sample Size	46.
Average	79694.7
Median	79779.8
Standard deviation	918.371
Standard error	135.406
Minimum	78009.1
Maximum	81923.3

Ta ble 4·3,4
$\theta_i \cdot S_i$ values

G	±1.15%
D	±0.13%
R	±0.40%
K	±0.50%
Rc	±0.10%
ΔF	±0.80%
N	±0.13%

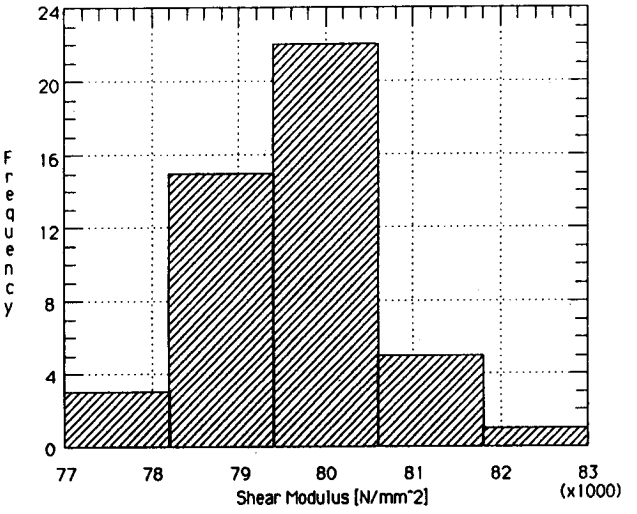


Fig. 4·3,1 Frequency Distribution of the Experimental Values of Shear Modulus

4.4 A Three-Dimensional Diffraction/Radiation Program

Following is the theoretical basis of a conventional 3D diffraction/radiation computer program for wave-induced motions and loads on large volume structures in regular waves:

incompressible fluid and irrotational flow,
linearized free surface and body boundary conditions,
linearized pressure and force expressions,
harmonic motions and loads,
zero Froude number.

Verification of a 3D diffraction/radiation program includes:

- Comparisons with analytical results for simple geometries and limiting values of the parameters. Examples are: McCamy & Fuchs theory for a vertical circular cylinder; asymptotic formulas for long wavelengths relative to the structure; and asymptotic formulas for small wavelengths.

- Verification of reciprocity and other analytical relations. Examples are: symmetry of coupled added mass and damping coefficients; Haskind relations for the wave-exciting forces and moments.

- Verification of relations between damping coefficients and radiated wave amplitudes according to conservation of energy.

- Systematic accuracy analysis. This includes a listing of the possible error sources.

In the FPS 2000-comparative studies referred to in Section 2, three sources of numerical errors were listed. They are panelling of the body surface, Green function calculation, and solution of equation system. The errors due to panelling were investigated by asking the participants to perform the calculations for a different number of panels and investigate the convergence of the linear and drift forces. It was assumed that the convergence or error ε_p due to panelling could be expressed as:

$$\varepsilon_p = \frac{| f_N - f_\infty |}{| f_\infty |} = K\left(\frac{1}{N}\right)^\alpha ,$$

where f_N is the computed value with N panels, and f_∞ is the value one would obtain if there were an infinite number of panels. K and α depend on the frequency, wave heading, response variable, shape of the body, and specific choice of panels. Large errors may occur if the size of the panels is not small enough to account for the local variations in the flow. This is, in general, important near the edges and corners, and, in particular, near the free surface for the drift forces. Similarly, the panel size should be small compared to the wave length. The convergence will not be the same between the two cases: using a combination of plane panels and unknown constants on each panel, and using another combination of curvilinear panels with a quadratic variation over the panels. Most of the results showed an α value close to 1, but there was a large variation in the K value. In some special cases, the results may converge to wrong values.

An example is the flow prediction near a sharp corner when not accounting for the singular behavior in the solution procedure. One important numerical source of error, due to the Green function evaluation, is associated with the specific manner by which the Rankine part (1/R) is integrated analytically over a panel. Errors due to a solution of the equation system are believed to be insignificant, except in the vicinity of irregular frequencies. Table 4·4,1 presents an example of convergence tests for added mass (A), and damping coefficients (B) for surge (11) and pitch (55), for the six-column TLP shown in Fig. 4·4,1 (Korsmeyer et al. 1988). If one assumes a constant, a linear or other type of polynomial variation of source density or velocity potential over panels adjacent to a sharp corner, the solution will always be in error at a panel adjacent to the sharp corner. However, correctly converging results will be obtained if the singular behavior of the velocity at the sharp corner is accounted for in the solution procedure.

Another example is the calculation of tangential velocity at an element. If we use Green's second identity to represent the velocity potential, approximate the body surface by plane quadrilateral elements (panels), and assume constant variation of the velocity potential over each element, the tangential velocity will always be in error at the element. The reason for this is the assumption that a constant variation of the velocity potential over a panel is inconsistent with finding the tangential velocity (i.e. tangential derivative of the velocity potential) at the element.

These two examples illustrate that convergence tests should include not only testing on the integrated quantities like added mass, damping, and exciting forces, but also tests on local behavior. The examples also illustrate that it is not sufficient merely to claim that results converge as the number of panels increases, but it is also necessary to provide an evaluation that the numerical modeling is consistent with what we want to calculate.

Table 4·4,1

	N	ω: 0.558	1.456	2.453	N	ω: 0.558	1.456	2.453
A_{11}	820	1.05085	1.30596	0.81857	448	1.07219	1.31550	0.85302
	1652	1.03811	1.29660	0.80328	1696	1.05451	1.31397	0.81659
	3188	1.04896	1.31097	0.80911	3744	1.04860	1.31041	0.80892
	6512	1.04208	1.30397	0.80283	6592	1.04629	1.30854	0.80606
	12608	1.04280	1.30548	0.80260				
B_{11}	820	0.02140	0.08641	0.31230	448	0.02177	0.08627	0.28130
	1652	0.02154	0.08467	0.30761	1696	0.02215	0.08587	0.30226
	3188	0.02206	0.08575	0.30638	3744	0.02217	0.08541	0.30333
	6512	0.02200	0.08480	0.30473	6592	0.02216	0.08516	0.30353
	12608	0.02209	0.08490	0.30442				
A_{55}	820	0.51783	0.51992	0.49196	448	0.53035	0.53107	0.50301
	1652	0.50239	0.50773	0.47758	1696	0.51733	0.52139	0.49147
	3188	0.51116	0.51563	0.48579	3744	0.51188	0.51668	0.48652
	6512	0.50473	0.51019	0.47990	6592	0.50915	0.51424	0.48402
	12608	0.50486	0.51030	0.48004				
B_{55}	820	0.00083	0.00482	0.00829	448	0.00100	0.00485	0.01025
	1652	0.00069	0.00496	0.00789	1696	0.00075	0.00503	0.00803
	3188	0.00071	0.00504	0.00752	3744	0.00069	0.00506	0.00759
	6512	0.00066	0.00506	0.00741	6592	0.00067	0.00507	0.00744
	12608	0.00065	0.00508	0.00733				

Added-mass (A) and damping (B) coefficients for surge (11) and pitch (55) for the six-column TLP shown in Figure 4.4,1. The left half of the table is for discretization shown in Figure 4.4,1. The right half is for a modified discretization with continuous azimuthal subdivisions on the columns and with the aspect-ratio of panels preserved for each value of N. (N=total number of panels.)

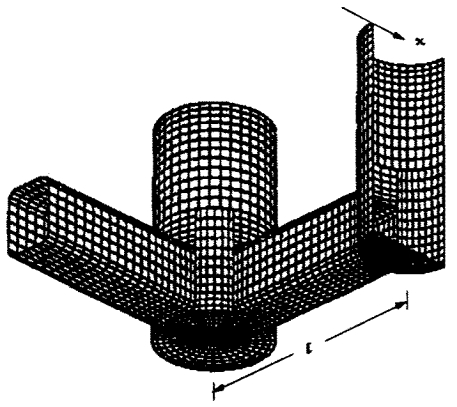


Figure 4.4,1 Submerged portion of one quadrant of the six-column TLP discretized with 3152 panels per quadrant (12,608 panels for the total structure). The coordinate system is defined with the longitudinal x-axis joining the axes of the two central columns as shown. The characteristic length used for nondimensional parameters is the distance between the axes of the central column and that of an adjacent corner, indicated by the dimension t. The other dimensions of this configuration are: draft=0.859t, length=1.897t (between axes of two adjacent corners), diameter of corner columns=0.455t, diameter of central columns=0.373t. The cross-sectional dimensions of the pontoon are depth=0.278t, breadth=0.207t, and corner-radius=0.038t.

4.5 A Strip Theory Program

A strip theory program for ship motions and loads has several similarities with a 3D diffraction/radiation program. The theoretical basis of a strip theory program is also incompressible and inviscid fluid, irrotational flow, linearized free surface and body boundary conditions, linearized pressure and force expressions, and harmonic motions and loads. However, the theory is not limited to zero Froude number. This means that the boundary conditions are different. In addition, a slender body assumption is made. There exist different strip theories. The theoretical basis of each strip method is the mathematical model of that specific strip theory. It specifies the boundary value problems to be solved, and how the solutions from the boundary value problems should be combined to obtain the added mass, damping and wave-excitation loads.

Verification of a strip theory program includes:

- Comparisons with analytical results for simple geometries and limiting values of the parameters. Examples are: a) circular cylinder results for added mass and damping by Ursell's theory; b) high frequency asymptotic values of added mass for Lewis form sections and by Schwartz-Cristoffel transformation for rectangular and triangular sections; and c) asymptotic formula for wave-excitation loads and motions at high and low frequencies.

- Verification of the reciprocity and analytical relations. Examples are: a) Timman-Newman relations for coupled added mass and damping coefficients; and b) 2D symmetry properties for coupled added mass and damping coefficients at zero speed.

- Relations between 2D damping coefficients and radiated wave amplitudes according to conservation of energy.

- Tests to confirm that the results converge as the number of panels or other discretization elements increases.

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III. CONCLUSIONS AND RECOMMENDATIONS

1. SUMMARY AND CONCLUSIONS

1.1 Measurements

A significant body of literature exists on the subject of uncertainty and error analysis of laboratory, test rig and full-scale measurement. Much of the literature is reviewed in this report and the progress to the development of an international standard is charted.

The accepted International Standards Organization (ISO) and American National Standards Institute (ANSI) methodology is wholly relevant to the work of ITTC and has been presented in this report as Guidelines for Uncertainty Analysis of Measurements in Section II.3.2. These Guidelines were distributed to Technical Committees in October 1988 and formed the basis for subsequent discussion and the development of examples. The principles have been applied to the contributions in Section II.4, where examples covering Resistance, Maneuvering, and Speed and Power trials are presented. The methods were found to be not difficult to employ, though the initial identification of all sources of error and the quantification of their likely elemental uncertainties inevitably promote much debate and consideration.

On the whole, however, the Panel concluded that there was little reason to prevent serious attempts at analysis of uncertainty in hydrodynamic measurements. In parallel with other engineering disciplines, the ITTC community should be encouraged to continue the initial work of the Panel.

1.2 Computational Methods

In contrast to the position on measurements, evidence of significant work on validation and uncertainty quantification of computational methods was much more difficult to find. Not only is progress in hydrodynamics little different from that in aeronautics, but the awareness of deficiencies in our understanding and the ability to provide assurance to users and clients is also very similar.

The Panel was sure, however, that the difficulty of the task should provide little excuse for not making a good (if incomplete) attempt. Examples of changed attitudes and creditable efforts were found in the new generation of papers submitted to the Journal of Fluids Engineering (ASME) and to the 5th International Conference on Numerical Ship Hydrodynamics.

In principle, the fundamental concepts contained in the Guidelines for Uncertainty Analysis of Measurements apply to Computational Analysis.

Clearly, the computation of the sensitivity of the final result to a particular data input or modeling assumption is relatively easy to determine. Nonetheless, the concepts of bias and randomness do create some confusion in this context and only time, thought and the particular experience of individuals will eventually clarify the issues.

The Guidelines in Section II.3.3 define the various facets in the total validation process and illustrate the nature of the considerations at each stage.

It is believed that future detailed studies by Technical Committees can greatly assist the progress of understanding and implementation by ITTC members.

2. DRAFT RECOMMENDATIONS

2.1 To the Conference

- Members should practice validation in their day-to-day operations to achieve benefits in quality assurance, technical communication, competitive advantage, image, reputation, and defense in litigation.

- The Conference should approve the Validation Panel Guidelines (Section II.3) for use by ITTC members.

- Implementation should be advanced by use of the Guidelines and through training programs.

- The Validation Panel should cease to exist, with continued validation activities to be undertaken by Technical Committees to address pertinent issues and concerns in their respective areas of expertise.

- An appropriate mechanism, such as a small advisory group, should be established under the supervision of the Executive Committee to support, discuss, record and communicate the development of the ITTC-relevant validation activities during the term of an ITTC, and to coordinate such activities of the Technical Committees.

2.2 For Future Technical Work

- Each Technical Committee should have a Validation Task in its work all the time. It should perform specific analyses, e.g., select one type of computer code and establish a standard procedure for verification and validation of such type of code. This should include specification of necessary types of tests and of ranges of input variables.

- Each Technical Committee should design and recommend the requirements for comparative/ benchmark experiments to assist validation of specific measurements or computer codes.

- Each Technical Committee should devote a separate section in its report for reviewing new validation work in its technical field.

- ITTC should collect a register of completed Uncertainty Analyses and benchmark data.

GEOGRAPHICAL AREAS
OF 19TH ITTC COUNTRIES AND MEMBER ORGANIZATIONS

Name of Region	Component countries (*Countries not otherwise represented	Number of Member Organizations and countries not otherwise represented		Number of Advisory Council Members	
		18th	19th	18th	19th
America	Argentina	1	1	–	–
	Brazil	1	1	–	–
	Canada	2	2	1	1
	*Chile	1	1	–	–
	*Ecuador	1	1	–	–
	*Mexico	1	–	–	–
	USA	11	11	4	4
	*Venezuela	1	1	–	–
East Asia	China	6	8	2	2
	Japan	16	17	5	5
	Korea	3	5	1	1
Eastern Europe	Bulgaria	1	1	1	1
	German Dem. Rep.	2	2	1	1
	Poland	3	3	1	1
	*Romania	1	1	–	–
	USSR	3	3	1	1
Northern Europe	Austria	1	1	1	1
	Belgium	1	1	–	–
	Fed. Rep. Germany	5	5	3	3
	Netherlands	2	2	1	1
Scandinavia	Denmark	1	1	1	1
	Finland	3	3	1	1
	Norway	1	1	1	1
	Sweden	2	2	1	1
Southern Europe	France	3	3	1	1
	Greece	1	1	–	–
	*Israel	1	1	–	–
	Italy	5	5	2	2
	Spain	1	2	1	1
	*Turkey	1	1	–	–
	Yugoslavia	1	1	1	1
UK et al.	*Australia	1	1	–	–
	India	3	3	–	–
	United Kingdom	5	5	3	3
		92	97	34	34