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Modelling Techniques for Dynamics of Ships [and Discussion]

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Modelling techniques for dynamics of ships

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I discuss techniques for the modelling of the dynamics of ships in an experimental tank. Advances in computational fluid dynamics have made the numerical tank a real possibility, and I discuss the relation between the numerical and the experimental tank. Current techniques for modelling rigid ships, i.e. the seakeeping test, and flexible ships are investigated. Finally, the future prospects of these techniques are discussed.

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1. The experimental and numerical tanks

The relationship between theory and experiment in marine fluid dynamics is shown in figure 1 (Takezawa 1988). Before computers became widely available experiments played an important role in design; only the tank test (a series or routine test) could give quantitative as well as qualitative information. Theoretical analysis only aided experiments or tank tests qualitatively. The only practically useful theory was ship motion theory, e.g. the strip method.

Supercomputers have facilitated great advances in computational fluid dynamics (CFD) and numerical tanks may soon be used for modelling seakeeping (Newman 1989). A Navier–Stokes equation solver has been developed that can be applied to gas–liquid two-phase flow (Miyata *et al.* 1988). If this solver was available for any Reynolds number, then the numerical tank would become viable.

If a numerical tank with CFD is defined as a pure numerical tank, then there is another numerical tank – the quasi-numerical tank – which uses various mathematical models: for instance, surface wave theory (based on potential theory), ship motion theory, models of vortex shedding around cylinders, propeller theory, etc. Of the ship motion theories, strip theory is the most practical and reliable; however, to improve these theories three-dimensional potential theory has been developed (Newman 1989).

As numerical simulation becomes more powerful, the tank test is declining in popularity. A towing tank may eventually be unnecessary and be replaced by the numerical tank, which is increasing in importance over experiments, which require much time and money. From now on research into the dynamics of ships in waves will rely upon the numerical tank test as a consequence of the widespread availability of supercomputers.

However, numerical tanks can be supplemented by experiments, which can be used to investigate areas in which numerical methods have not yet been applied. This kind of experiment will not require fancy huge water tanks such as the ones listed in the International Towing Tank Conference (ITTC) catalogue; however, it will require a small tank supported by advanced and highly intelligent technology, and advanced facilities with enough precession.

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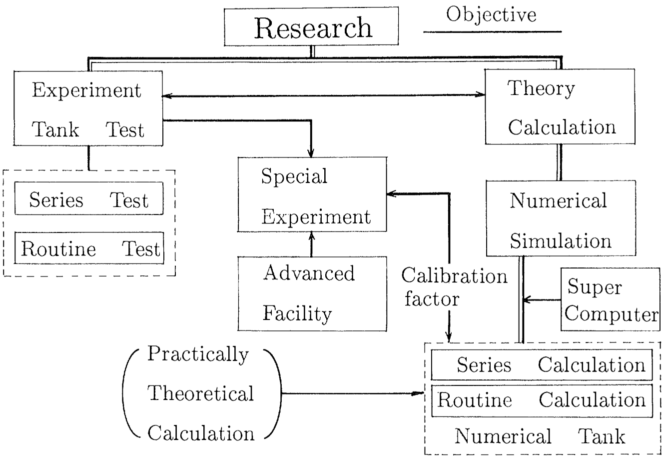


Figure 1. Experimental tank and numerical tank (Takewaza 1988).

2. Validation of experiments

The ITTC established the Panel of Validation in 1987 in which the validation of both numerical calculations and experiments is investigated (Morgan & Lin 1989).

Although the accuracies ensured by towing tank tests have been discussed (Yamazaki *et al.* 1983), there is no corresponding discussion for seakeeping. Because the objectives of seakeeping tests are various and the accuracy required for experiments depends on the objectives, all methods of validation cannot be discussed in the same manner. Besides, the accuracy ensured by tests of the dynamics of ships in waves is less strict that that for powering tests in calm water, and I mention the validation of the experiments concerning the dynamics of ships in waves. The errors for the total measurement systems are listed in figure 2, and these are similar to those for towing tank tests.

The dynamics of ships in waves may be categorized into stability tests in waves, resistance and propulsion tests in waves, wave load tests and operability or workability tests in waves. Because the tests are so varied there has as yet been no unified uncertainty analysis for tests in waves. I expect the ITTC to establish a unified uncertainty analysis even for seakeeping experiments.

3. Dynamics of rigid ships

Modelling techniques dating from before the 1970s are summarized by van Lammeren *et al.* (1957), van Lammeren (1963), Takezawa (1969) and Takezawa *et al.* (1977).

Epochs of modelling techniques of experiments in seakeeping tanks since the 1970s are listed here. The square tank with an X–Y carriage is one of the model tanks, which facilitated experiments involving six degrees of freedom of the ship's motion and a six-mode wave load on a model ship in oblique waves with forward speed (Motora *et al.* 1970). The wave-making system is a snake-type, multisegmented wave generator which generates designed directional waves in a square tank and now also in a narrow towing tank (Takezawa *et al.* 1989) (see figure 3). Now we can carry out

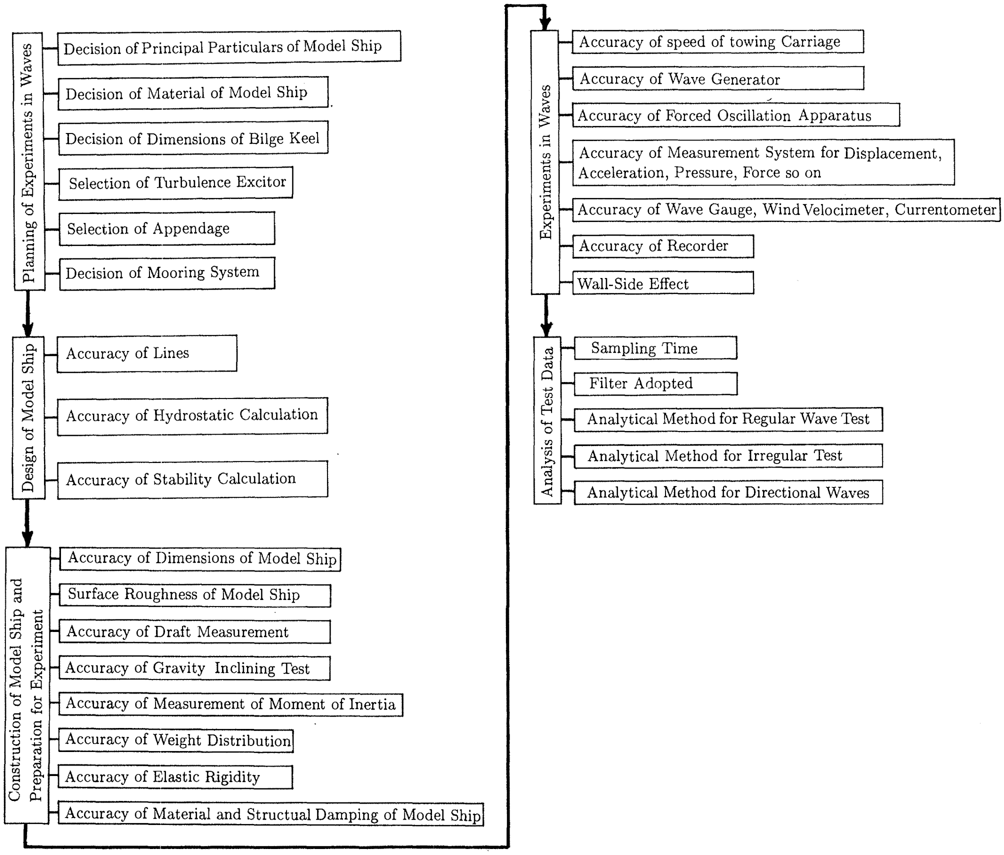


Figure 2. Error evaluation items for dynamics of ships in waves.

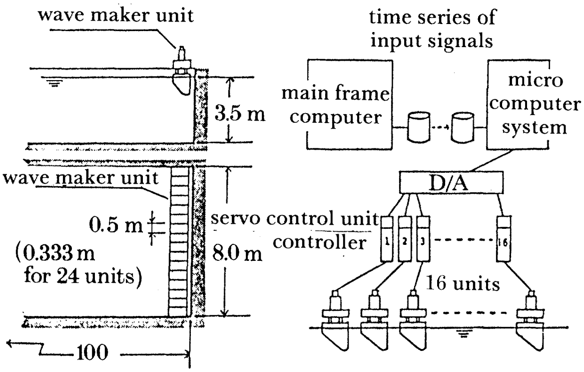


Figure 3. Arrangement of the multi-unit wave maker and control system diagram in the narrow tank (Takewaza *et al.* 1989).

experiments on ship motion with forward speed in directional waves. The accuracy in the construction of model ships has been improved since numerically controlled machine tools became available, whereas fibre-reinforced plastics made it possible to get the model's moment of inertia close to the corresponding moment of inertia of the full-scale ship. The advanced technology of mechatronics has been successfully

Figure 4

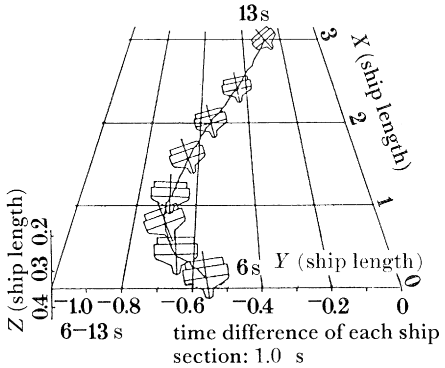


Figure 5

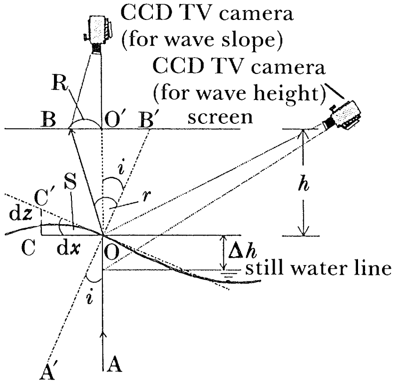


Figure 4. Trajectory of capsizing model measured by optical tracking system (Hasegawa 1990).

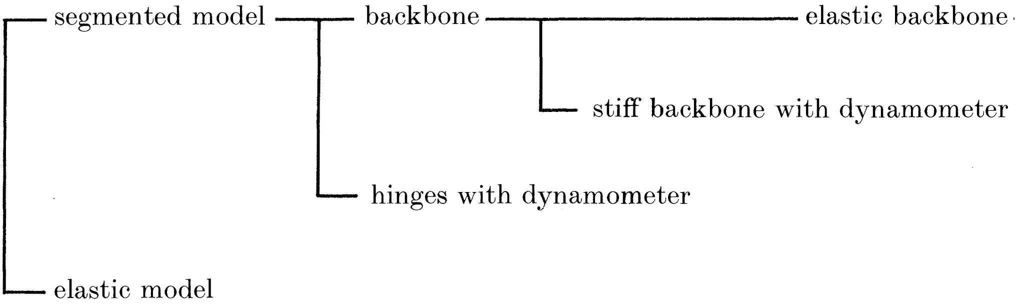
Figure 5. Measuring principle of wave elevation and wave slopes on the laser wave surface probe (Takewaza *et al.* 1989).

applied to an experimental apparatus as a result of the continued development of servo-mechanisms and microprocessors. Applications are the forced oscillation apparatus (Fujii *et al.* 1971), the forced oscillation apparatus for low-frequency motions in waves (Kinoshita *et al.* 1987), the added resistance measurement system in waves (Kyozuka *et al.* 1986), the wind load simulator (Takezawa *et al.* 1988) and the automatic tracking system for the self-propelled model ship (Rutgersson *et al.* 1987). A servo-type wave gauge using mechatronics when attached to a towing carriage can measure the encounter wave height with a high accuracy. Measurement instrumentation, data recording and the acquisition system have become very much more accurate because of the application of electronics. As to recent measuring systems, it seems that the data analysis system is becoming complicated and highly advanced by using microprocessors, whereas the measuring system itself is getting simpler and more robust; examples are the optical position sensor and the six-component dynamometer. The optical position sensor has contributed very much to research on low-frequency motion of a moored floating body because the frictional damping of the sensor is so small that it has succeeded in measuring low-frequency motion due to the second-order hydrodynamic force with an accuracy that is high even for a small model. The capsizing of model ships can also be measured by a similar kind of sensor called the X–Y tracker (Hasegawa 1990; Ishida *et al.* 1990) (see figure 4). Recently Takezawa *et al.* (1989) developed a laser-type wave gauge that can measure both wave height and wave slope, i.e. directional waves (figure 5). These modelling techniques are all derived from optoelectronics. Computer graphics make it possible to visualize and interpret the experimental results.

It seems that the progress of modelling techniques for seakeeping is founded upon several technologies: microprocessors, computers, mechatronics, optoelectronics, etc. These technologies are all advanced and the modelling techniques are now characterized by computer assisted tests (CATS).

4. Dynamics of flexible ships

Bishop & Price (1979) have contributed greatly to the study of the structural dynamics of ships. From the point of view of seakeeping, structural dynamics has long been an important subject, especially because there have occurred many accidents to navy ships as a result of severe weather conditions. Moreover, the increase in size and speed of ships has caused structural damage as a result of slammings. Slamming and whipping became important factors, and, furthermore, springing was found to occur in less severe sea conditions. In 1974 Bishop and Price held the symposium on the dynamics of marine vehicles and structures in waves. As a result of the breaking away of the bows of large ore carriers during their winter voyages in the seas around Japan, research into the stuctural dynamics of ships was intensively carried out. In this section I describe the modelling techniques relevant to this research that have been developed since 1974 (for such techniques before 1974, see Wereldsma (1974)). These techniques can be categorized as follows:



The similarity law of the elastic response model test was given by Bishop & Price (1980) as follows, where the subscripts m and s indicate the model and full scale respectively. By Froude's law,

$$U_m = U_s/\Lambda_L^{\frac{1}{2}}, \tag{1}$$

where $\Lambda_L = L_s/L_m$ is a geometrical scale factor. Time t is

$$t_m = t_s/\Lambda_L^{\frac{1}{2}}. \tag{2}$$

The shear stiffness kAG is

$$(kAG)_m = (kAG)_s/\Lambda_L^3. \tag{3}$$

The bending stiffness EI is

$$(EI)_m = (EI)_s/\Lambda_L^5. \tag{4}$$

The damping coefficients of the model and full scale are equal because they are non-dimensional.

The model test comprises two parts: the motion test in waves and the forced oscillation test in still water.

The modes of the forced oscillation tests are longitudinal and transverse bending, and torsion and axial modes. The reaction forces are measured so that the generalized added masses and the damping coefficients are found. In the linearized potential theory, if the fluid reaction is $F_{lk,ij}$ for the kth oscillation of the j-mode, the following reciprocal theorem is derived (Maeda 1980):

$$F^{+}_{lk,ij}/\rho\omega^2\xi_{l,i} = F^{-}_{kl,ji}/\rho\omega^2\xi_{k,j}. \tag{5}$$

Here, the superscript '$+$'/'$-$' denotes that the ship advances along the positive/negative x-axis. The subscripts 'i,j' stand for the modes of oscillation and 'k,l' denote the order of oscillation. ρ, ω and ξ are the density of fluid, the circular frequency of oscillation and the amplitude of oscillation, respectively. This relation

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Figure 6

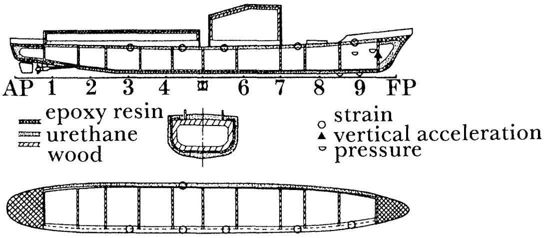

Figure 7

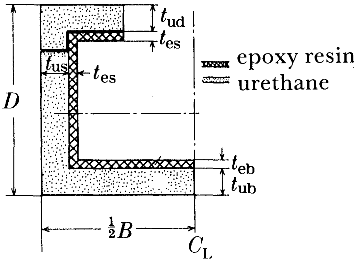

Figure 6. Profile of elastic model (Watanabe *et al.* 1988).

Figure 7. Schematic diagram of the cross section of elastic model (Watanabe *et al.* 1988).

holds even for arbitrary hull forms, i.e. those which are asymmetric in transverse and/or longitudinal directions, if the ship speed is zero. If the ship advances with forward speed, then the assumptions of slender ships or thin ships are required. There exists also the Haskend–Chertock–Ogilvie relation between the wave load and Kochin function given as follows (Ogilvie 1973):

$$E^{+}_{\bar{k},j}(\alpha)/\rho g a = H^{-}_{\bar{k},j}(K,\alpha+\pi). \tag{6}$$

Here $E(\alpha)$ is the generalized wave exciting forces of the incident waves propagating at an angle α. $H^{-}_{\bar{k},j}(K,\alpha+\pi)$ is the Kochin function, corresponding to the case that the ship advances in the negative x direction. The forced oscillation model test in still water to validate these relations by using elastic models or segmented models has rarely been performed (Gerritsma *et al.* 1963).

I now give two examples of a model test using the fully elastic model. A fully elastic container ship model was first constructed by using foamed vinyl chloride (Fukasawa 1981), which has a scale ratio of 58.3 and a Young's modulus of 15 kg mm^{-2}, so that it is possible to use a fairly thick plate. The logarithmic damping coefficient is $\delta = 0.142$. Measurements were made of ship motions (pitch, roll and yaw), strains on the deck, accelerations on the deck of the bow and pressures on the flare of the bow.

The second example is the patrol boat model that Watanabe *et al.* (1988) constructed with composite materials of epoxy resin and urethane foam. The length of the model is $L_{\mathrm{p}} = 4.33$ m, the scale ratio is $\Lambda_L = 16.22$ and the Young's moduli of the epoxy resin and the urethane foam are $E = 142$ kg mm^{-2} and $E = 2.0$ kg mm^{-2}, respectively. The logarithmic damping coefficient is $\delta = 0.13$ for the model, while $\delta = 0.106$ for the full scale. The epoxy resin is used as the main stiffener and the urethane foam for body fairing. The measuring points and the sectional configuration of the model are shown in figures 6 and 7.

The advantage of the fully elastic model is that the model tests can be carried out in the model tank, and these can include even the elastic behaviours of the prototype in waves since it can fulfil not only the geometrical similarity but also the elastic similarity. Besides, it is possible not only to measure the wave loads (even if it is difficult to measure them in the full-scale case), but also to perform the model tests in severe sea states in which it is too dangerous to perform a full-scale test. However, some defects are also found. The structural damping is bigger than that of full scale and the creep of the material occurs easily. It is desired to develop a material of small stiffness and structural damping.

The examples of segmented models with elastic backbones are given by Kaneko *et al.* (1986) and Masuda *et al.* (1985). This method has a long history and was also used by Wachnik *et al.* (1963). The advantage of this system is its simplicity, so that it is appropriate for the elastic response test of a small model. Changing the stiffness of the backbone enables two kinds of model tests. For the higher stiffness, the effect of the elastic responses to the wave impacts is small and thus only the fluctuating wave exciting forces can be picked up. With the lower stiffness, to that of full scale, it is possible to measure the wave loads including the elastic responses of ships. Masuda *et al.* (1985) used the steel as the backbone material and Kaneko *et al.* (1986) used aluminium as the backbone. In the measurement of wave loads, strain gauges are attached on the metal beam of the backbone. With the elastic backbone method it is easy to change longitudinal stiffnesses but difficult to adjust at the same time the corresponding transverse bending vibration and the torsional vibration stiffnesses in similitude with the full scale.

Wereldsma (1974) used a stiff dynamometer-attached backbone to the segmented model. This method has the same advantages and defects as the method in which the segmented model is directly connected by dynamometers at each hinge point. It is possible to accurately measure the wave loads of at most six modes with the use of the wave loads acting on each segment according to the capability of the dynamometer.

Examples of segmented models connected by hinges to dynamometers are as follows. Maeda *et al.* (1979) measured the wave loads acting on the connected points of a three-segmented offshore structure. Takahashi *et al.* (1986) applied this method to a ship with a ultra-shallow draft and a wide breadth. Ueno *et al.* (1990) applied the same method to a multi-segmented ship.

The super-large floating offshore structure, such as the floating offshore airport, has a relatively small stiffness and elastic responses. Model tests of responses in waves for this kind of super-large floating structure were performed at the Ship Research Institute of Japan (Ando *et al.* 1983; SRI 1985). Generally speaking the modelling techniques of flexible ships are now available according to their objectives.

5. Prospects of modelling techniques

The prospects of modelling techniques for the experimental test of dynamics of ships in waves are discussed here. The object of the experimental tank in the future will be to validate CFD and the coupling of CFD, while there will be no need for modern huge water tanks. The tank will be smaller and use smaller size model ships. The tank will be supported by modelling techniques derived from advanced technology.

Design and construction of ships in the future will be undertaken using a computer integrated manufacturing system (CIMS), and the design stage will be planned by considering the construction stage. The research plan will follow the total plan and the plan for numerical tank and experimental tank will follow this research plan. Experience and know-how were important for experimental planning in the experimental tank. This experience could be replaced by artificial intelligence (AI), such as expert systems, which are expected to be support systems for experiment planning. This experiment planning should include rational uncertainty analysis.

With regard to unmanned system for experiment, we can look forward to realizing an autonomous experimental system which includes mechatronics and neural network.

The following prospects of experimental facilities are anticipated: a combined environment simulation tank which can generate any combination of unsteady environmental condition (such as waves, winds and currents) with designed spectrum; a tank for deep sea technology; a tank which can guarantee continuously long-time experiments without wall-side effects and without reflected wave effects. Deep sea technology may require the development of non-isotropic scaling techniques, i.e. different scaling between the horizontal and vertical planes, because it is impossible to carry out the same scaling experiment in both horizontal and vertical planes if the full-scale water depth is more than 1–2 km.

Measuring systems, and data acquisition, recording and processing systems are becoming more computer assisted. Present computer assisted tests are rather fragile, because they fail even if only one line is broken. But any future CAT system must be robust. At present electronic equipment and automated data acquisition systems are so reliable that engineers may lose touch with the halfway house of data processing; however, there is in prospect a human friendly interface which points to a hands-on approach to data processing.

Advanced technologies which will be utilized are as follows: the laser gyroscope, the high-resolution television, mechatronics, micromachine technology, advanced materials which may make both the elastic rigidity and the structural damping of a model ship similar to the corresponding full-scale ones. Sensors for measurement systems, such as pressure, acceleration, strain and so on, will become more sensitive and more accurate at the same time as becoming smaller. Light and reliable optical fibres will be used for data transmission which will contribute to the reduction in the size of the facilities. Biosensor may be able to detect the mental processes of human beings, such as comfortability on a floating vessel.

6. Conclusion

Modelling techniques for dynamics of ships in waves have advanced in step with the development of electronics since 1970s. Small-size, high-speed data processing and cheaper computers attain real-time high-speed and accurate experimental data analysis. Hence the tank test is known as a computer assisted test. The basic aim of modern modelling techniques is to derive important information with the assistance of powerful computers from simple and raw mass data. If tests in transient water waves are available, much experimental time may be saved. Tests in directional waves are now feasible. Moreover, dynamics of model ships can be measured by non-compact-type instrumentation to towing carriage according to the development of high-accuracy opto-electronics. NC cutting machines may be used to make a mould of model ships which gives high-precision and high-speed manufacturing. As mentioned above, CAT can give us now a large quantity of data with a high accuracy and almost in real time.

The problem is now how to extract important information from that large amount of data, and how to make final decisions. At this moment the most important point is to clarify the object of the research, in which the role of experiment and theory should be clearly defined. Future research will be based mainly on numerical tanks supported by highly reliable theory, while the small experimental tank, assisted by advanced technologies, will be used to validate the theory and carry out one-of-a-kind experiments. That is to say, modelling techniques in future will be used – taking into account the corresponding theory to realize the object of the research and considering uncertainty analysis for the rational validation – according to highly reliable experiment planning.

This fundamental concept of modelling techniques reminds us of W. Froude, to whom we have been paying great respect as the father of the modelling techniques in Naval Architecture (Yoshioka 1985).

I acknowledge Dr I. Watanabe and Mr Y. Okawa of the Ship Research Institute of Japan.

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Discussion

J. E. Ffowcs Williams (*University of Cambridge, U.K.*). I was most interested by Professor Maeda's description of a really versatile ship simulation facility in which physical modelling is integrated with modern digital data acquisition and handling equipment. That seems a great improvement on past technology and offers prospects of knowing detailed features of a kind previously beyond experimental reach. It seems to be a pity to saddle the computer-generated view of the problem with the restrictive terminology of the past. The name 'numerical tank' suggests to me the danger that tank-restricted methodology will persist and hinder the pace of progress. It also carries the implication that computers can (or should) soon replace the testing tank – and that I doubt; the complications of free surface flows at very high Reynolds numbers are likely to defy direct numerical simulation for many years (decades) yet. Computer simulation will I think complement the testing tank and not replace it and I would prefer to avoid the restrictive view of numerical modelling that the tank nomenclature implies.

On a more definite matter, to what extent is the physical modelling of the ship's structural flexibility necessary? If the purpose of testing is to determine the loads on the structure, then I doubt if influence of ship flexibility on those loads is significant in the circumstances discussed so far in this meeting, circumstances in which the relative motion between the ship and the water due to the ambient sea state are much more violent than any deflection associated movements. I confess to being puzzled about Sessions III's heading, 'flexible ships'. It does seem to me that all the required information on the surface wave loading of a ship is available from a rigid ship model, and the complication of modelling the structural response is unnecessary.

H. Maeda. Professor Ffowcs Williams points out that the terminology 'numerical tank' is not definite and misleading. As Dr A. Silverleaf comments, this terminology is derived from the ITTC and we need not worry about that. Numerical simulation always includes some assumptions and must be a restricted methodology. I agree with his comments that computer simulation will complement the experimental simulation and not replace it. He also discussed the influence of ship flexibility on wave loads and he thought the complication of modelling the structural response is unnecessary. He is right when he considers wave loads on container ships or tankers which do not include slamming effects. However, if we think of slamming effects, then maximum wave loads should be derived from coupled motion of waves and flexible ship. This maximum wave load must be larger than that of a rigid ship model (see Fukasawa *et al.* 1981). There is another example in which ship flexibility plays important role. A 300 m Great Lakes ore carrier has relatively narrow breadth compared with its length because it passes through narrow locks of The Great Lakes and Saint Lawrence river. The natural period of two-node vibration of the ore carrier is very low, about 3 s because of the flexibility. Around this period, radiation forces such as added mass varies drastically. Then we could not neglect the effect of ship flexibility (Maeda 1980).

A. Silverleaf (*INTRA, Teddington, U.K.*). Professor Maeda has given us an admirable account of some recent developments in both CFD and in techniques for experiments with models. He argued that theoretical calculations would become the dominant approach for solving many practical ship design problems, and that, in future, the main role of model experiments would be to validate theory. The coming together of theory and experiment has long been the ambition of those engaged in ship hydrodynamics, and model experiments have been used to validate theory for many years; indeed, I spent several months almost 50 years ago on forced rolling experiments with ship models and with models of ship stabilizer fins (including some in cavitating conditions) for just that purpose. So the basic object do not change – only the analytical and experimental tools available. He has shown the adoption of the best techniques and equipment from other fields is continuing vigorously, with evident success. Steady evolution, not dramatic revolution, is the natural process.

Professor Ffowcs Williams queried the name 'towing tank' for the kind of experiment facility described by Professor Maeda. He need not worry: almost its only present use is in the title of the ITTC, adopted in 1954 as a convenient compromise to replace the more cumbersome, but then more accurate name, International Conference of Ship Tank Superintendents. Now, individual establishments are called ship model laboratories, experiment tanks, or something similar. Whatever name they adopt, such model laboratories (large as well as small) will be required as long as laboratories are needed for other branches of applied science.

H. Maeda. The advent of the compact high-speed computer and supercomputer greatly improved turnaround time and reliability of analysis of experimental data, and the importance of larger experimental tanks has diminished.