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Report on the First International Workshop on Water Waves and Floating Bodies

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A workshop was held at MIT in February 1986 for specialists performing theoretical research on the interactions of water waves with floating or submerged bodies. The principal applications of this field are related to ship hydrodynamics and to wave loadings on offshore platform. In addition to the traditional approach based on linearization of the wave and body motions, substantial progress has been made on nonlinear problems including both analytical and numerical studies. Subsequent workshops are planned on an annual basis.

1. Introduction

The interaction of water waves with floating or submerged bodies has been an active area of fluid mechanics since the time of Lord Kelvin and J. H. Michell. Naval architects, seeking analytical methods to predict phenomena such as the wave resistance of ships and their motions in a seaway, have worked together with applied mathematicians who are attracted to this field. During the past 20–30 years the number of workers has grown significantly, with the emergence of parallel applications in the field of offshore engineering including the analysis of wave interactions with large structures intended for oil exploration, recovery and production. Activity in the latter field has been most intense in the countries bordering the North Sea, and in the United States.

The common technical theme of ship hydrodynamics and offshore engineering is the development of analytical and computational methods for predicting the hydrodynamic interactions of surface waves with floating or submerged bodies. Potential theory is applicable in most cases, and the boundary conditions are well known, but the free-surface boundary condition is a severe complication in solving this class of problems. The use of numerical techniques and solutions has been an obvious feature in the past two decades. However, as with other branches of fluid mechanics, ever-larger computing facilities are not a panacea and continued developments must rest on a combination of numerical and analytical efforts, with appropriate guidance from experiments.

In order to provide a forum for informal discussions of fundamental theoretical research in this area, of mutal interest to engineers and scientists, the authors have initiated an annual series of workshops. The first of these was held at MIT on 16–19 February 1986. A total of 37 papers were selected on the basis of submitted extended abstracts, with contributions from younger workers and research students as well as from established experts. A list of all speakers and the titles of their talks is given in the Appendix. To preserve an atmosphere conducive to informal discussion, attendance was limited to the authors of the accepted papers and the session chairmen.

Two special lectures on industrial applications were presented by L. Schwartz and R. Van Hooff. Schwartz described a problem of current interest to oil companies, in which one liquid is used to push another out of a porous oil-bearing formation (DeGregoria & Schwartz 1986). When the pusher fluid is the less viscous of the two the fluid interface is unstable and the resulting flow exhibits 'viscous fingers'. Under suitable approximations the Hele-Shaw equations can be derived requiring the solution of two potential-flow problems separated by a moving boundary. A numerical technique was described giving results in qualitative agreement with experiments for a steady-state propagating finger. Several analogies with water-wave problems were noted in the discussion.

The lecture by Van Hooff was devoted to the role of theoretical wave-loading predictions on the design of large offshore structures, with special emphasis on the design of the unique tension-leg platform in the Hutton Field of the North Sea. Van Hooff emphasized the practical difficulty of incorporating the growing base of scientific knowledge into offshore design, and the need for good communication between the research community and design engineers.

In the following sections we summarize five major topics covered at the Workshop.

2. Time- and frequency-domain formulations

The tone of the Workshop was set by J. V. Wehausen in a stimulating opening lecture in which familiar ideas from linear systems analysis were used to link causality, in the time domain, and the radiation condition in the frequency domain. Starting from the impulse response function, assumed to vanish for negative time, Wehausen showed that the motion of a body in response to a general exciting force is causal provided a radiation condition holds in the frequency domain. An alternative approach suggested by F. Ursell requires the assumption of boundedness of the velocity potential in the time domain, in addition to the initial conditions. Ursell noted that the same dilemma occurs in other boundary-value problems, such as the diffusion equation.

One advantage of the time-domain approach, emphasized by F. T. Korsmeyer, is that the computational burden of matrix inversion is substantially less than in the frequency domain. Thus, for complicated bodies requiring a large number of panels for their description, it may be more effective to compute the time-domain solution and use Fourier transforms to obtain the results in the frequency domain. With respect to the accuracy of this numerical Fourier transformation, it is important to distinguish between two canonical problems in the time domain: (i) where an initial displacement or velocity of the body is given and its subsequent motion is determined in the absence of external forces, analogous to the classical Cauchy–Poisson problem in water-wave theory (Ursell, 1964); and (ii) where the body is given an impulsive motion and then held fixed, with the subsequent force to be determined, as in the determination of the impulse-response function in simpler linear systems (Wehausen 1971). The second of these two solutions appears to be more useful, insofar as it can be Fourier-transformed numerically (Newman 1985) to yield the damping and added-mass coefficients in the frequency domain. The first canonical solution is inferior in this respect since the frequency content is dominated by the resonant response of the body.

3. Linear analysis of multiple bodies

In the conventional linear frequency-domain approach, numerical techniques based on boundary-integral equations or finite-element methods can be used to describe wave radiation and diffraction, but a large number of panels or elements are required when the body shape is complicated (Yeung 1982). When N multiple bodies interact, the number of panels or elements must be increased in proportion to N. The 'wide-spacing' approximation, based on the assumption that each interacting body is in the far field of the others and subject only to (locally) plane waves radiated and diffracted by the other bodies, has been used with considerable success in two and three dimensions (Ohkusu 1974). The practical validity of this approximation is remarkable, extending well beyond the limit where the spacing is large compared with the wavelength.

If the wide-spacing assumption is used without further approximation to describe an array of N bodies, an N-dimensional matrix equation follows for the mutal interactions among all members of the array (Simon 1982). This approach has been extended by Kagemoto & Yue (1986) to include an arbitrary number M of both radiating and evanescent eigenfunctions in the far-field representation of each body, thereby achieving (as M tends to infinity) an exact representation of each body and its multiple interactions with the others. In practice with M finite the matrix representation of the interactions is $N \times M$ in dimension. A new approximation was described by D. K. Yue based upon the assumption that N is large; this facilitates the analysis of large arrays of bodies of identical geometry with an arbitrary number of eigenfunctions for each body. In the special case $M = 1$, Yue's work represents an asymptotic approximation of the wide-spacing approach for large N. When N tends to infinity the results for a periodic array are obtained.

Closely related to the 'wide-spacing' approximation is the analysis of wave interactions in adjacent fluid domains, partially separated by a barrier, where the far-field plane waves reflected and transmitted by the barrier are matched to determine the motion in each domain. This approach was followed in work described by P. McIver & D. V. Evans to predict the eigenfrequencies of sloshing modes in a rectangular tank with a vertical baffle. Good agreement was shown with a full linear analysis, confirming the validity of the basic approximation in another context. It was noted in discussion that this problem has important application to the dynamics of road tankers.

Yet another extension of the wide-spacing approximation was described by S. R. Breit, the analysis of wave interactions between a pair of catamaran hulls with each hull represented by a slender body and the radiated waves from the opposite hull assumed to be plane. A pair of coupled integral equations result for the effective source strength along each hull. Numerical results based on this approach are in good agreement with more complete results from a three-dimensional panel computation for a pair of spheroids separated by one diameter at their midsections.

Further impetus for studying wave diffraction by multiple bodies has come from the unexpected subsidence of the sea bottom in the Ekofisk Field of the North Sea. This subsidence, which so far amounts to about 3 m, decreases the freeboard of several platforms and increases their vulnerability to storm damage. Various schemes have been proposed to overcome or alleviate this problem, and the most economical appears to be the construction of an array of breakwaters consisting of submerged elongated vessels. An approximate analysis of such an array was described by T. Vinje & A. Nestegard in which strip theory is used along each vessel and an outer three-dimensional wavefield is used to represent the interactions. By arranging each structure in the array in an appropriate manner, it is possible to refract incident waves away from the existing platforms. This scheme depends for its success on the predominance of major storm waves from only one direction. In the discussion E. Mehlum described two alternative analyses of the same array which use fully three-dimensional numerical solutions and a short-wavelength ray theory. The large scale and time constraints of this project are apparent, and theoretical guidance is vital.

4. Second-order effects

Extension of the linear frequency-domain analysis to include second-order contributions to the perturbation expansion in wave height and body motions permits the analysis of the steady drift force exerted on a body in monochromatic waves, and the corresponding long-period excitation when two wave components with slightly different frequencies are present. These phenomena are specially important in the vertical motions of vessels with small waterplane areas, and in the horizontal dynamics of vessels restrained by weak elastic moorings, since in both cases the restoring force is small and the period of resonant response is long (Ogilvie 1983). The steady second-order loads in a plane monochromatic wave system can be determined exactly from the first-order velocity potential, but the complete determination of the second-order force due to two discrete wave components requires the velocity potential to be solved to second order. The second-order solution satisfies an inhomogeneous free-surface boundary condition, and special care is required in the direction where the radiated and incident waves are opposed. This direction also causes difficulty in the derivation of the second-order radiation condition.

A comprehensive analysis of the latter problem was described by B. Molin for a body with axisymmetric form about a vertical axis. Additional computations of the second-order forces for monochromatic waves were noted by various participants. P. F. Wang described a time-domain formulation of the second -order problem where the radiation condition is replaced by a more obvious initial condition, but questions were raised regarding the appropriate transient representation of the incident-wave system.

A broad discussion of low-frequency horizontal motions in a seaway was presented by O. M. Faltinsen, who emphasized the importance of the second-order damping and response, in addition to the wave excitation force. Depending on the geometrical configuration and scale, viscous forces due to separation and unsteady vorticity must also be accounted for. For a slender vessel such as a moored ship, the slowly varying surge motion about a zero mean can be interpreted as a quasi-steady ship speed and the resulting damping effect can be determined from the low-speed limit of the added resistance for steady forward velocity in a wave system. Outstanding questions of practical importance include the effects of a three-dimensional irregular seaway, interactions with a steady current, and the presence of external forces due to wind loading or thrusters.

5. Ship waves

The steady-state wave motion due to uniform translation of a ship is one of the oldest and most challenging problems in this field. The presence of an $O(1)$ streaming velocity past the body introduces convective terms in the linearized free-surface condition, and raises fundamental questions regarding the validity of the linearization itself. Interactions with the boundary layer and separated wake raise complementary issues regarding the interpretation and validity of the theoretical results.

Interest in this topic has been especially strong in Japan, where numerous stimulating and fundamental contributions have originated (Society of Naval Architects of Japan 1976). Following that tradition, Y. Doi presented an analytical and experimental study of wave interactions with the viscous wake behind a ship hull. Photographs of the free surface at closely spaced Froude numbers reveal striking changes in the wave pattern, which are attributed to such interactions, as well as a downstream surface wake with a turbulent appearance where the waves are largely suppressed.

Many efforts have been made to develop short-wavelength asymptotic theories based on the assumption that the Froude number is small, although there are fundamental difficulties with the analysis, and possible questions regarding the practical validity. The general approach is to perturb about the zero-Froude-number double-body flow past the ship hull and its image above the undisturbed free surface, using ray theory to follow the waves in the non-uniform convective field of that flow (Keller 1979; Tulin 1984). F. J. Brandsma presented recent work where the rays emanate solely from the bow of the ship. There is a singular point, where stagnation occurs in the double-body flow, and it is not clear if significant wave generation will occur along the ship downstream from the bow or at the stern.

An ambitious numerical study was reported by P. S. Jensen where the boundary-integral-equation method is used with elementary Rankine sources distributed over a closed surface including the ship hull, free surface, and a suitable control surface across the wake downstream. Various tests have been conducted in two and three dimensions to facilitate the implementation of a radiation condition downstream.

The more classical approach, based on the use of a free-surface source potential or Green function which satisfies the linear free-surface condition, has been impeded by the complexity of this function in its usual representation as a double Fourier integral. In a new technique for the evaluation of the double integral, described by J. N. Newman, three-dimensional expansions in Chebyshev polynomials are used to provide systematic approximations of high accuracy. A hybrid scheme may prove to be useful where a direct numerical approach such as Jensen's is employed to develop a fully nonlinear inner solution, and the linear Green function is used at an appropriate matching surface to ensure that waves radiated from the nonlinear inner domain are not reflected.

One of the most active nonlinear topics in this field has been motivated by observations of unsteady waves propagated ahead of a steady moving disturbance in a shallow channel. Initially these waves were observed with ship models in towing tanks near the critical Froude number based on the fluid depth, where the phase and group velocities are equal, but more detailed experiments have revealed the presence of precursor waves both below and above the transcritical regime. Several theories have been put forth to explain this phenomenon as an example of runaway solitons. T. Y. Wu summarized work in this area and described the current effort in his own group based on numerical solutions of generalized Boussinesq and Korteweg–de Vries equations including forcing by a pressure acting on the free surface, and by a moving body on the bottom of the channel. An extension from a two-dimensional Korteweg–de Vries formulation to a three-dimensional solution based on the Kadomtsev–Petviashvilli equation was described by T. R. Akylas. The relative merits of this approach, and the domains of its applicability, were discussed by J. V. Wehausen, who with co-workers has applied the Green–Naghdi attractor theory to the same problem (Ertekin, Webster & Wehausen 1984), as well as C. C. Mei (Mei 1986) who has used the nonlinear Schrödinger equation to analyse a slender ship hull. Each of these different theories confirms the observed phenomenon in the transcritical regime, and some also reveal weaker precursor waves outside that regime. A striking feature is that the precursor waves are nearly plane, not only for the two-dimensional situation in a narrow tank but also for waves generated by a concentrated disturbance in a wide channel.

6. Large-amplitude waves or motions

The availability of large-scale computers has made it possible in recent years to solve radiation problems in the time domain, without approximation of the nonlinear free-surface condition. Boundary-integral equations are used with elementary Rankine singularities, and the solution is obtained in discrete time steps starting from prescribed initial conditions. This yields a sequence of mixed boundary value problems with Neumann conditions on the body surface and Dirichlet conditions on the free surface. Early work used a simple truncation of the computational domain at large distances from the body, but this leads to the reflection of radiated waves and breakdown of the solution after relatively short durations of time (Faltinsen 1977; Isaacson 1982). Recent developments to overcome this problem have been based on the assumption of spatial periodicity (Vinje & Brevig 1980), or on the matching of a nonlinear inner solution to a linear outer solution in three dimensions (Lin, Newman & Yue 1984).

The periodicity assumption is used in work described by J. Martin to analyse the nonlinear behaviour of a semi-submersible vessel consisting of two submerged buoyant pontoons and relatively small vertical supports piercing the free surface. This computation is streamlined by inverting the matrix for the singularities on the submerged body surface, which is time independent in a moving reference frame, and thereby reducing the size of the subsequent matrix inversion for each time step to the elements on the free surface. A significant feature of Martin's computations is a mean rotation of the vessel with the leeward pontoon at a deeper submergence; this situation is expected from experiments but has not been so clearly displayed from second-order perturbation analysis.

Time-stepping solutions in a rectangular domain that simulates a wave tank with prescribed wavemaker motions were described by J. L. K. Chan, and also by D. G. Dommermuth & D. K. Yue. In the latter work the measurement of the wavemaker displacement in special experiments has been used as the computational input, and striking agreement has been obtained between the computational and experimental values of the free-surface profile and velocity field for steep breaking waves practically up to the point where the plunging crest touches the free surface and the fluid domain ceases to be simply connected. The restriction to two-dimensional motion, and the use of a supercomputer, make it possible to extend the length of the computational domain sufficiently to avoid reflections from the far vertical boundary within the time duration needed to describe the breaking process.

Steady waves of large amplitude resulting from the escape of a thin jet of air from the side of a hovercraft were described by E. O. Tuck. As the jet moves along the free surface stationary waves are formed in both the air and water. Unlike the time-stepping solutions, which can be developed from an initial state of rest, Tuck's nonlinear solution is determined by iteration. A stability analysis which extends this work may shed further light on the interaction between a static hovercraft and the ocean surface.

7. Conclusions

In this report we have touched upon the main themes of the Workshop. In addition there were a number of individual presentations in other areas that provoked considerable interest and discussion and which could well provide the themes for future workshops. The report edited by Breit (1986) contains extended abstracts of each talk and a summary of the discussion that took place at the Workshop.

On behalf of all participants, we thank the US National Science Foundation for financial support of the First International Workshop on Water Waves and Floating Bodies. The Second Workshop will be held from 16–19 March 1987 at the University of Bristol.

Appendix. List of papers

Agnon, Y. & Mei, C. C. (MIT, USA) Nonlinear resonance of long shelf waves by incident short waves.

Akylas, T. R. & Katsis, C. (MIT, USA) Excitation of three-dimensional nonlinear waves by ships moving in shallow water.

Aranha, J. A. P. (Sao Paulo, Brazil) Trapped wave and non-linear resonance in a semi-submersible.

Brandsma, F. J. (Delft, Netherlands) The ray method for nonlinear ship waves.

Breit, S. R. (MIT, USA) Surface-wave interaction between adjacent slender bodies.

Chan, J. L. K. & Calisal, S. M. (Vancouver, Canada) Numerical towing tank for ship motion.

Doi, Y. (Hiroshima, Japan) & Kajitani, H. (Tokyo, Japan) Study on characteristics of stern waves including viscous effects.

Dommermuth, D. G. & Yue, D. K. (MIT, USA) Numerical methods for nonlinear two-dimensional waves: regriding versus smoothing.

Faltinsen, O. M. (Trondheim, Norway) Slow-drift phenomena in irregular waves.

Hearn, G. E. (Newcastle, UK) Higher order methods of hydrodynamic analysis.

Jensen, P. S. (Lyngby, Denmark) On the use of Rankine source potential in the ship wave problem.

Korsmeyer, F. T. (MIT, USA) On the solution of the radiation problem in the time domain.

Lee, S. C. (Stevens Institute, USA) A preliminary study on the hydrodynamic interactions between the wave, current and body.

Liu, Y. W. (Delaware, USA) A simplified boundary integral method for two-dimensional floating body problem.

Marshall, K. & Evans, D. V. (Bristol, UK) Wave problems with space-dependent boundary conditions.

Martin, J. (Edinburgh, UK) Evolution of semi-submersible motion in waves.

Martin, P. A. (Manchester, UK) Null-field methods for floating cylinders.

McIver, M. (University College London, UK) Diffraction of water waves by a moored horizontal flat plate.

McIver, P. (Brunel, UK) & Evans, D. V. (Bristol, UK) Sloshing frequencies in a rectangular tank with a baffle.

Mei, C. C., Hara, T. & Naciri, M. (MIT, USA) Resonant scattering by periodic structures.

Molin, B. (IFP, France) Second-order double frequency loads and motions for 3D bodies.

Newman, J. N. (MIT, USA) On the wave resistance Green function.

Papanikolaou, A. (Athens, Greece) On the nonlinear wave forces acting on partially or fully submerged cylinders in waves.

Pousin, J., Verriere, M. & Lenoir, M. (ENSTA, France) Study of the application of the localized finite element method for the resolution of the 2D Neumann–Kelvin problem.

Schwartz, L. (Exxon, Annandale, New Jersey, USA) The nonlinear evolution of viscous fingers – a water-wave problem in disguise.

Sclavounos, P. D. (MIT, USA) Recent advances in unified theory.

Stiassnie, M. (Technion, Israel) Energy calculations based on the modified Zakharov equation.
Troesch, A. (Ann Arbor, USA) A theoretical investigation of wall reflections.
Tuck, E. O. & Grundy, I. H. (Adelaide, Australia) Waves generated by airflow from a stationary hovercraft.
Ursell, F. (Manchester, UK) On the decay of wave motion in water of finite depth.
Van Hooff, R. (Conoco, Houston, USA) Dissemination of research results.
Vinje, T. (A. S. Veritec, Norway) & Nestegard, A. (Defense Research Establishment, Norway) Changes in the wave elevation caused by under-water ridges.
Wang, P. F. (MIT, USA) Transient second-order diffraction by a vertical cylinder using the Weber transform.
Wehausen, J. V. (Berkeley, USA) The radiation condition and causality.
Wu, T. Y. (Caltech, USA) Periodic generation of solitons by steady moving bodies.
Wu, X. J. & Price, W. G. (Brunel, UK) Appearance and disappearance of irregular frequencies in wave-structure interaction problems.
Yue, D. K. (MIT, USA) & Kagemoto, H. (Ship Research Institute, Japan) Wave forces on a platform supported on a large number of floating legs.

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