CHAPTER ONE HUNDRED NINETY

A SIMULATION METHOD FOR SMALL CRAFT HARBOUR MODELS

by

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ABSTRACT

A simulation method is presented to improve small craft harbour design by studying the behaviour of moored vessels in small craft harbours, using physical modelling in medium size wave basins, available at most laboratories. Instead of carrying the study in an agitation model **with moored vessel** models and built in a large wave basin at a large geometric scale, it is performed in two consecutive models of different scales, in a medium size basin. Transfer functions of vessel movements and mooring and fender forces are determined in the first model, for representative types of vessels moored alternately at a solitary berth, under simulated inside harbour conditions and for various sea states and directions. Near berth wave spectra are obtained in the second (agitation) model for sea states covering the local climate. Integration of the wave spectra with the transfer functions leads to response spectra of vessel movements and forces. Finally, maximum movements and forces are determined from the response spectra and are used together with limiting criteria and the long term wave statistics to choose the optimum configuration of: harbour layout, types of berth structures and mooring and fendering systems.

INTRODUCTION

The design of small craft harbours has usually been based on agitation models in which only waves were measured inside and in the surroundings of the simulated breakwaters' layout of a small craft harbour model, for various incident wave heights, periods and directions. The types of wave disturbance studied were short wave disturbance induced by gravity waves (periods 3-30 sec) and seiche disturbance induced by infragravity waves (periods 30-180 sec). The wave disturbance data required in the agitation model have been used to determine the optimum layout and the optimum types of structures of the designed small craft harbour, on the basis of empirical rules regarding allowable wave heights and current strength. Such rules, specifying only the maximum allowable wave height near a harbour berth were presented by Dunham and Finn (4), Le Mehaute (7), Mercer et al. (8). It was clear that such criteria could be used only as general guidance for small craft harbour design but that they were not sufficient for an optimum design

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including harbour layout, inner harbour configuration, type of berth structure for each berth and mooring and fendering systems. Therefore, it is not suprising that the importance of simulating moored vessel behaviour in the model for reliable design of large commercial harbours has been recognized many years ago Vasco Costa(13), and nowadays has become the usual modelling procedure. Althought the same importance was attributed to simulating moored vessels for the design of small craft harbours, its application was performed only in few small craft harbour studies, e.g. Isaacson and Mercer (5). Most of the model studies of small craft harbours however, continued to be carried out in agitation models lacking the presence of moored vessel models, Stickland (12). The lack of moored vessels in the simulated models seems to be due to the difficulty to fulfill simultaneously the two following requirements:

a) The harbour model should cover the area of the harbour and its surroundings. Hence, it has to be built at a relatively small geometric scale (1:80 - 1:125) in order to fit into a medium size wave basin (available at most laboratories).

b) The models of small vessels (sailboats, lighters, trawlers, patrol boats, etc.) have to be made at relatively large geometric scales (1:20 - 1:50). Since such vessels are light and have small displacements (compared to commercial ships) this requirement is necessary in order to allow the correct simulation of loading conditions (displacement, mass distributions) and natural periods of oscillation(roll,pitch) as well as accurate measurements of vessel movements and of forces in the mooring lines and into the berth fenders.

Obviously, these requirements could be fulfilled only when a large size wave basin was available. Even then, vessel models were usually not used, due to the much increased costs for building the model and carrying out the study of the small craft harbour at a large scale relatively to the expenses of a model built at a small geometric scale (about 4:1).

This paper presents a simulation method which includes the study of moored small craft vessels, but which allows to carry out the model study in a medium size basin and at competitive costs performance, relatively to those of an agitation model without vessel models. (Costs about 1.5 - 2 times more than those of an agitation model). Furthermore, using this simulation method, the simultaneous fulfillment of the above requirements a) and b) is no longer necessary. This method was applied at CAMERI for the design study of a relatively large fishing harbour.

DESCRIPTION OF THE MODEL SIMULATION METHOD

General Concept

Two basic concepts stay behind the present simulation method. The first one, known as the Froude-Kriloff hypothesis (see Korvin-Kroukovsky (6)) states that the effect of a vessel located in a wave field on that wave field can be considered negligible. Consequently, the measurements of the wave field in an agitation model are expected to provide all the necessary information required to forecast the behaviour of a vessel

in that wave field, if the transfer functions relating the input waves with the response behaviour of the vessel are known.
The second concept, known as the Froude hypothesis on linear superposition, states that the resulting amplitudes of movements of a vessel located in an irregular wave field can be determined by linear superposition of the separate contributions of regular waves of corresponding wave energy at each frequency band to that existing in the irregular field at that frequency band.
On the basis of these two concepts, the simulation procedure assumes that the results which would be obtained from a physical model with moored vessel models built at a large geometric scale (say 1:30-1:50), may also be sufficiently accurate determined in the case of a small craft harbour built in shallow water, by dividing the study into two separate physical models and by combining analytically the results of these two studies.

The first model would be a "moored seakeeping model study" in which the transfer functions of vessel movements and mooring and fender forces are determined for various wave conditions, while the second model would be an "agitation model" in which near-berth wave spectra are measured and logged for various harbour configurations and for various representative sea states covering the wave climate at the site of the proposed small craft barbour. The application of the measured wave spectra on the transfer functions determined, would provide response spectra of moored vessel movements and mooring and fender forces, from which maximum movements and forces can be determined. The combination of the results obtained for various types of vessels, and for various types of harbour configurations due to various sea states, with the limiting criteria of vessel movements, mooring and fender forces and harbour entrance wave heights and with the statistics of the long term wave climate, would allow the choice of the optimum configuration of breakwaters layout, berth structures and mooring and fendering systems and would ensure the optimum operability and safety of the small craft harbour design.
Since each of the above mentioned models can be carried out separately, each of them can be performed at its optimum geometric scale. Each one would usually fit in a medium size wave basin and they may be carried out in two consecutive testing stages.
The general simulation procedure is schematically presented in Figure 1.

Moored Seakeeping Model Study

In order to obtain the transfer functions of the vessel movements and of the mooring and fender forces for relevant vessels representing the fleet determined to be serviced by the proposed fishing harbour, a moored seakeeping model study was carried out. The model was built in a wave tank of limited overall dimensions (24x 26m), at a geometric scale of 1:50, large enough for the simulation of the vessels considered. Two types of vessels were chosen for the study, namely a trawler of 800 DWT and a tuna boat of 400 DWT. Each of the vessel models was calibrated for two loading conditions, one of ballast at departure, the other of laden at arrival.
The vessel models were alternately moored at a solitary berth in a number of alternative mooring and fendering systems of varying stiffness,

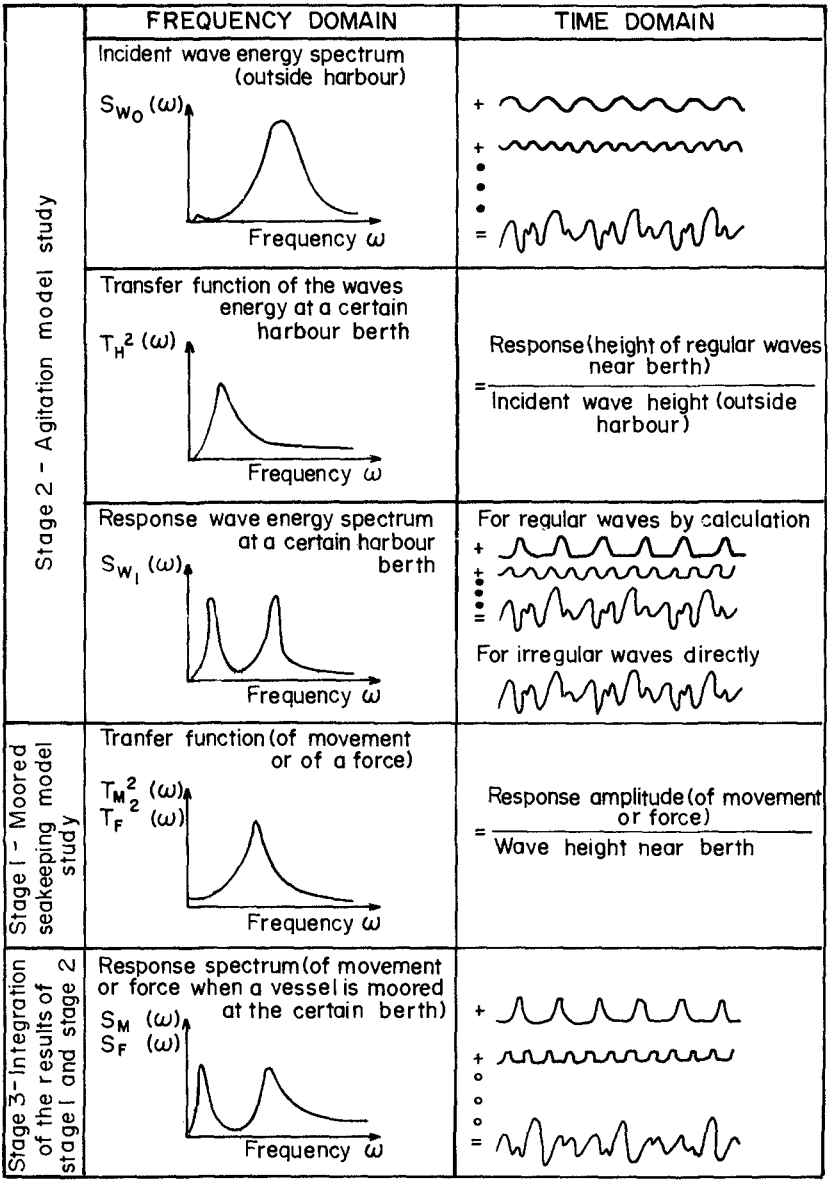

Fig. 1. Schematic description of the procedure to obtain response spectra of vessel movements and forces in mooring lines and in fenders by linear superposition.

while the berth structure was alternately changed to represent three types of berth structure: an open structure on piles, an impervious wave reflecting sheet pile structure and an impervious but wave absorbing rubble slope beneath a piles supported structure. The models of mooring lines and fenders were made in such a way as to correctly represent the nonlinear load deflection curves of the mooring lines and the nonlinear load compression curves of the fender units. For the model of a mooring line the correct load deflection was achieved by attaching one of the ends of a stiff thread representing the mooring line to two linear springs located on the vessel model and the other end to a force transducer located on the berth. Of the two springs only one worked at the beginning while after a certain loading was achieved both springs worked together (see Fig. 2).
For the model of a fender unit the non linear load compression curve was obtained also with the aid of two linear springs located one inside the other and working in a similar way as the springs of a mooring line model (see Fig. 3).
Vessel movements were measured with the aid of rotational potentiometers, forces were measured by means of linear displacement voltage transducers and waves were measured by resistance type wave gauges, (see Fig. 7).
Unidirectional incident waves of regular and irregular type were separately generated in transient water depth. The incident waves were adequately shoaled by sloping bottom and then were propagated over a constant water depth section on which the solitary berth was located. The water depth at that section corresponded to the designed water depth inside the proposed harbour. In this way the direct excitation of near-berth shoaled waves on the moored vessel model was obtained for various conditions tested.
The measured movements, forces and wave data were statistically analyzed in real time and logged on magnetic media by a minicomputer system which controlled also the wave generation.
The tests with regular waves covered the wave periods range corresponding to gravity and infragravity waves (3-30 sec and 30-60 sec). The tests with irregular waves were performed to study the additional effects of drift forces (induced by wave groups) on the moored vessels, because these forces are not obtained with regular waves. For both wave types a few wave heights (calibrated in the absence of vessels) were tested with various configurations. The wave heights range was from 0.2 m to 0.8 m (prototype). Care was taken to remove parasitic components of the waves generated. Under these circumstances, the response amplitude operators (RAO), i.e. the transfer functions of the vessel movements and forces were determined for three angles of wave incidence considered relevant in this study (0^o, 30^o, 60^o) relative to the vessel longitudinal axis.

Agitation Model Study

After the moored seakeeping model study was finished, an agitation model in fix bed was built in the same wave tank at a geometric scale of 1:100. The model covered the harbour and its surroundings in order to allow the correct simulation of boundary conditions.
Various sea states, covering the local climate at the site of the proposed harbour were generated using unidirectional irregular waves (in situ recorded) for various configurations (i.e. for various layouts

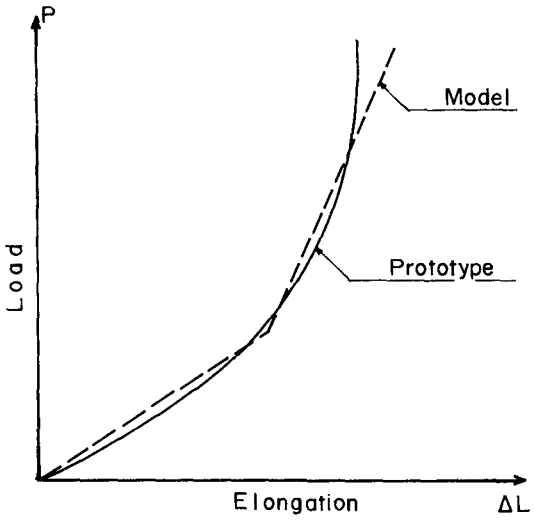

Fig. 2. Schematic modelling of load-elongation characteristics of a mooring line.

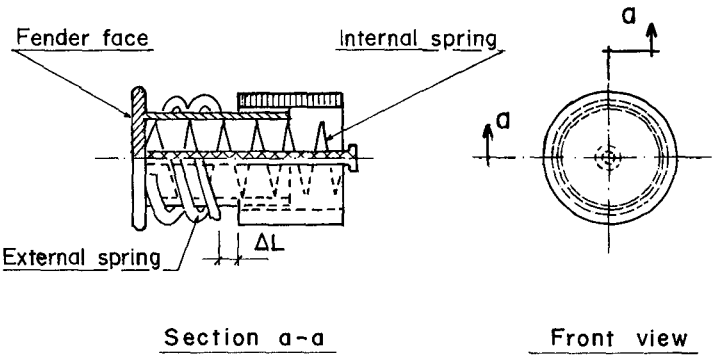

Fig. 3. Schematic description of a fender model.

of the protecting breakwaters, for various inner harbour layouts of the berths and for various types of berth structure). The wave data measured at the various harbour berths as well as these measured at the harbour entrance and at various locations in the surroundings of the harbour were statistically processed in real time and were logged on magnetic media by a minicomputer system. Off line spectral processing of the logged wave data yielded the response wave spectra of the harbour at every berth as induced by the various incident deep water sea states. These response wave spectra of the harbour to the external wave excitation became the input wave spectra which would be applied on vessels moored at the harbour berths. The wave spectra measured for various wave conditions at a majority of harbour berths showed wave energy concentration in two frequency ranges: one with less energy in the high frequency range, the other with equal or more energy in the low frequency range.

It is estimated that the concentration of wave energy in the low frequency range is related to the interaction between the wave groups with the harbour geometry.
Examples of incident wave spectra in deep water and in shallow water and for the corresponding inside harbour wave spectra, are shown for four sea states in Fig. 4, 5 and 6.
Since the wave field inside the harbour is composed of incident waves entering the harbour and of reflected waves from the harbour structures, the directional spectrum of the waves at any harbour berth would be important for the correct determination of the response spectra of the vessel movements and forces.
However, for the present model directional spectra could not be measured and consequently some simplifications have been adopted. Firstly, it was realized that the direction of wave incidence inside the harbour at a berth is almost independent of the direction of incidence of the waves outside harbour. Secondly, the general wave pattern in the harbour could be determined visually by photography. From the analysis of pictures, it was observed that the waves approaching any berth of the harbour have mainly a two dimensional nature (as can be seen in Fig. 8). Furthermore, the variance spectrum of the waves measured at each berth included already possible reflected waves. On the basis of these remarks it was possible to proceed further with the determination of the response spectra of the vessel movements and forces, considering the waves approaching any berth to behave like unidirectional waves.

Determination of Response Spectra of Vessel Movements and Forces

Assuming the Froude hypothesis mentioned before to be true under the excitation of relatively small waves (below 1 m significant height), the behaviour of the oscillating system composed by a vessel and its moorings and fenders may be considered linear. Consequently, one may obtain in such a case the response spectra of the various movements and forces according to the following formula:

$$(1) \qquad S_R(f) = T^2(f) \cdot S_W(f).$$

where: f - frequency; $S_R(f)$ - response variance spectrum of a movement or force; $S_W(f)$ - wave energy (variance) spectrum measured at a certain berth for a certain sea state and harbour layout; T(f) - transfer

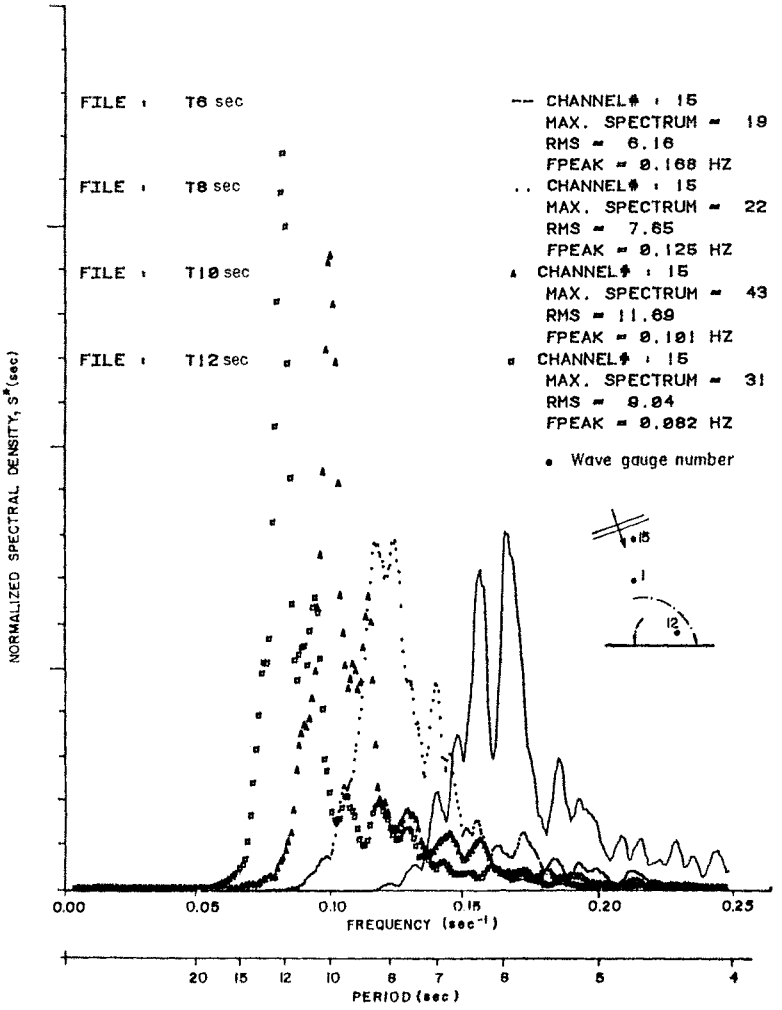

Fig. 4. Incident deep water wave spectra for four peak periods generated and measured in agitation model.

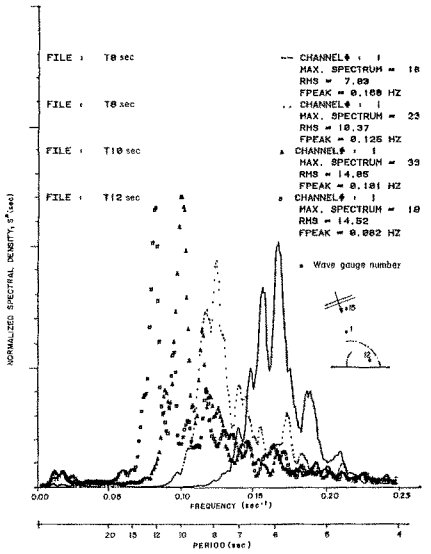

Fig. 5. Shallow water wave spectra in front of harbour entrance measured in agitation model.

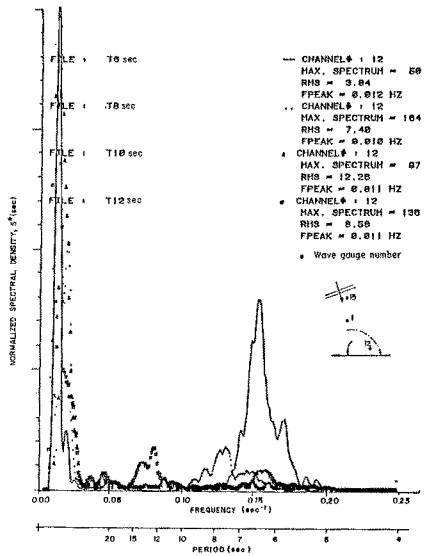

Fig. 6. Example of inside harbour near berth wave spectra obtained in agitation model.

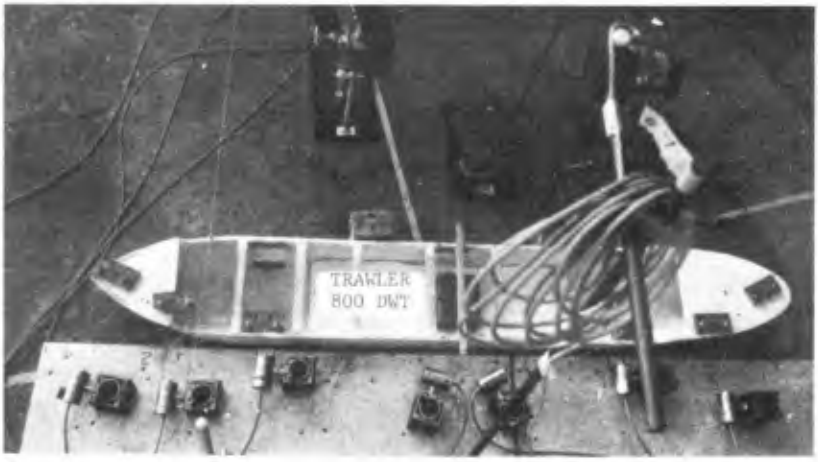

Fig. 7. Instrumentation set-up used in moored seakeeping model study.

Fig. 8. Wave incidence pattern observed in agitation model.

function of a movement or of a mooring or fender force.

A problen arose in the evaluation of the response spectrum regarding the choice of the correct transfer function, among the three transfer functions obtained for the three directions of wave incidence.
The logical procedure would be to determine the optimum orientation of the harbour berths on the basis of the values of the response amplitude operators (RAO) of the transfer functions of the predominant vessel movements. However, in the present study the berth orientations were predetermined by the designers on the basis of backland constraints. In view of these conditions it was decided to use for every movement or force of a vessel, only one transfer function, possessing the largest RAO values among those obtained for the three wave directions in the moored seakeeping model. Care was taken not to use the function obtained for a wave direction which was unreasonable in view of the wave pattern observed by photography. Still, the transfer functions obtained in this way lacked the contribution of the additional effects induced inside the harbour by the wave groups. Nevertheless, these effects could be discarded in the case of a small craft harbour because of the following two reasons:

a) The effect of drift forces induced by wave groups inside the harbour was in general small because the wave energy of the short waves was small too.

b) The spectral energies of the long waves induced in the harbour at the various berths were in general of the same order of magnitude or greater than the spectral energies of the short waves (see Fig.6). Therefore, the direct effect of the long waves was in general much larger than the one induced by the drift forces.

However, if the spectral energy would be larger than that in the low frequency range, the contribution of the drift forces becomes important and can not be neglected. In such a case, it would be necessary to determine transfer functions on the basis of irregular waves to add the contribution of the second order drift forces, but this was not the case in

Consequently, in the case of a small craft harbour located in shallow water the proposed simulation method was applicable and the response spectra were estimated to lead to slightly conservative results. An example of a response spectrum is shown in Fig. 9 for surge movement.

Evaluation of Maximum Movements and Forces

From the response spectra, maximum vessel movements and mooring and fender forces occurring in various sea states and layouts were determined by the following procedure: Firstly, for each response spectrum obtained, the spectral variance σ_R^2 and the zero crossing wave period T_Z of the response were evaluated using the formulas:

$$\sigma_R^2 = \int_0^\infty S_R(f)\, df \qquad (2)$$

and

$$T_z \tilde{=} T_{m_{o,2}} = \sqrt{m_o/m_2} \qquad (3)$$

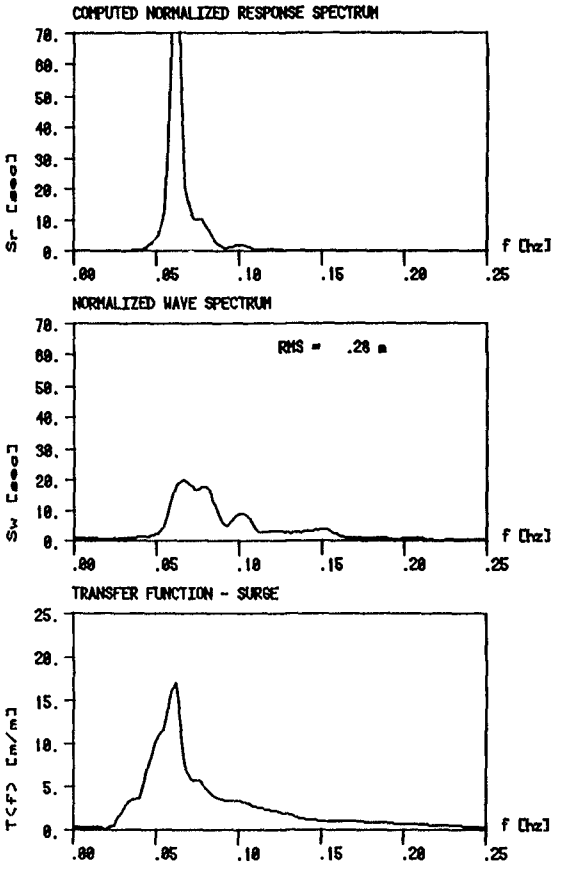

Fig. 9. Example of computer plot of computed response spectrum for surge movement (trawler vessel, full)

where $T_{m_{o,2}}$ is the spectral estimate of the zero crossing period and m_o and m_2 are the zeroth and second spectral moments of the response. Secondly, assuming a quasi-stationary sea state to prevail for a time period t, the average number of reversals (N) of a movement or force, was obtained from

$$(4) \quad N = t/T_z$$

Finally, assuming the movements and the forces during a quasi-stationary sea state to be Rayleigh distributed the maximum value of the response R_{max} was determined from the formula (Ochi (9)):

$$(5) \quad R_{max} = \sigma_R \left(\frac{1}{2} \ln N\right)^{1/2}$$

Though the assumption of Rayleigh distribution for mooring and fender forces is not quite true due to their non linear characteristics, it was estimated that this assumption led to conservative values.
A problem arose regarding the determination of maximum values for the many cases of two peaked response spectra. To solve this, it was decided to divide the response spectrum into two separate response spectra, one covering the high frequency range and the other covering the low frequency range and treat them as individual spectra, following the procedure outlined above. The maximum value of the response spectrum was obtained in this case by the summation of the individual maximum values obtained from the two divisions of the response spectrum.

HARBOUR OPTIMIZATION

Limiting Criteria

In order to determine limiting criteria regarding maximum allowable values of vessel movements and mooring and fender forces for safe operation at the harbour berths, a literature survey and discussions with a number of skippers and marina operators were carried out.
Limiting values regarding mooring and fender forces were presented by mooring lines manufacturers (Samson Ocean Systems (10), British Ropes (2)) and by PIANC (9), while limiting values of vessel movements are presented by Bruun (3). The discussions conducted led to the conclusion that beside the forces in moorings and fenders, the safety of mooring and loading or unloading operations is affected more by crew behaviour on vessel than by the amplitudes of vessel movements, though the latter are usually assumed to determine the crew behaviour. However, as shown by various studies of human behaviour during aircraft flight or seakeeping (e.g. Arwas and Rolnick (1)), the main factor in influencing human behaviour is the acceleration of the body and not the body velocity of movement.
After studying the information collected, the following criteria have been established as safety limit criteria.

- maximum linear acceleration : 0.4 m/sec^2
- maximum angular acceleration : 2.0 deg/sec^2
- maximum peak to peak roll : 6.0 degress
- maximum force in a mooring : 20% of breaking load
- maximum force in a fender : 60% of ultimate load

Here the movement limitation for roll was needed to prevent

entanglement of vessel masts while mooring side by side.

In order to determine maximum accelerations, response spectra of the accelerations corresponding to the six vessel movements were evaluated. The method described previously on response spectra was used, by applying the following formula:

$$(6) \quad S_a(f)=(2\pi f)^4 \cdot T^2(f) \cdot S_W(f)$$

where: $S_a(f)$ - acceleration response variance spectrum. Maximum accelerations were obtained assuming again the values to follow the Rayleigh distribution.

Determination of Yearly Average Operability

The maximum values obtained were combined with the wave statistics and the above criteria, yielding average yearly operabilities at every berth for the various layouts. From these results, the optimum harbour configuration was chosen.

CONCLUSIONS

A relatively inexpensive simulation method has been derived for the study of small craft harbours. This is estimated to allow sufficiently reliable determination of optimum harbour layout (breakwaters, quays) and optimum type of structure for each berth, in respect to safe operational conditions for the vessels serviced by the small craft harbour, using small to medium size wave basins which are available at most laboratories. In order to further increase its reliability a model study has been initiated at CAMERI, to compare this method with the results of direct measurements of vessel behaviour in a harbour model.

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