# ASPECTS OF OCEAN ENGINEERING WHICH ARE RELEVANT FOR THE ITTC: A REVIEW WITH EMPHASIS ON MODELLING OF SEA CONDITIONS

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## 1. INTRODUCTION

In the past decade there has been a very rapid growth in many new areas of marine technology which have come to be known collectively as ocean engineering. As a result many of the laboratories represented at the ITTC with facilities built mainly for conventional ship model testing and associated research are now heavily engaged in meeting quite new types of demand.

The intention of this paper is first to review in an ITTC perspective the general nature of the new requirements both for technological development which has a bearing on the Committee structure, and for facilities. Attention will then be concentrated on problems of modelling sea conditions in which the present author has a special interest. The word 'modelling' is here used to denote both functional representation of actual sea states and techniques of generating them in the laboratory and the opportunity will be taken to report some of the author's own recent work in these 2 areas which has particular relevance to ocean engineering.

Before proceeding further it will be helpful to define more clearly what is meant here by ocean engineering. In its most general sense it can embrace the whole of marine technology including the range of ship model testing and related research which has traditionally been the main business of towing tanks. For the present purpose however it is used to denote specifically the recent engineering developments mainly associated with offshore resource recovery to which the term is commonly applied and which though very diverse in nature generally involve structures designed for operation at fixed stations. In the past 10 years or so these have generated a new pattern of demand for the services of laboratories represented by the ITTC and indeed of related hydraulics laboratories under the 'umbrella' of the 'International Association for Hydraulics Research (IAHR)', on a scale which calls for a serious review of the present range of Technical Committee remits and of available facilities.

Regarding the question of Technical Committees, it is an outstanding feature of ocean engineering that a wide range of skills is needed with considerable emphasis on mechanical and civil engineering, mathematics, instrumentation and data processing as well as fluid mechanics and naval architecture. The present list of Committee titles is:-

Resistance, Performance, Propeller, Cavitation, Manoeuvrability, Seakeeping, Presentation.

These have not been changed in fact in the past 10 years and so are still restricted to the traditional topics of naval architecture. It is possible that many of the new requirements can be accommodated within the present Committee structure provided that the membership adequately covers the relevant specialist knowledge, but the present author believes that some change is needed. Major new topics which need to be covered include for example, 'Fluid Loading of Structures', 'Station Keeping', Offshore Operations' and 'Submersibles'. It is of course a matter for the Executive Committee to consider whether and if so how such new areas should be accommodated within the ITTC. Perhaps the simplest approach would be to form a Committee with the title 'Ocean Engineering' and a general remit to cover the subject matter of the present discussion session, namely "Aspects of Ocean Engineering which are relevant to the ITTC". The contents of the various contributions to this discussion should indeed offer a good starting point for the work of such a Committee.

The present contribution will concentrate on facility requirements for ocean engineering research with particular attention to problems of defining and modelling sea conditions, drawing on experience at the National Maritime Institute and reporting some of the author's own recent work.

As already noted ocean engineering is largely concerned with structures designed for operation at fixed stations whereas historically and according to its name the ITTC has been mainly concerned with towing tanks for testing ships in motion. This point may be underlined by referring to the ITTC catalogue of the particulars of facilities available in 1963 (published in the Proceedings of the 10th (ITTC Reference 1)) which shows a count of 102 towing tanks and only 15 seakeeping basins. It is true that the ITTC catalogue does not include the many flumes and wave tanks in hydraulics laboratories which are being used for ocean engineering experiments but most of these were originally intended mainly for coastal engineering applications and are rather shallow for testing offshore structures. It is also true that a number of new seakeeping basins have been built since 1963. Nonetheless it must be said that in spite of the extent and importance of the demand there are still relatively few facilities which have been purpose built for ocean engineering work.

In these circumstances, although in many cases existing facilities including towing tanks are accommodating most of this new demand with reasonable success, the time seems ripe for a systematic study of requirements and ways of ensuring that they are adequately matched by experimental capability.

## 2. REVIEW OF REQUIREMENTS

It would be unrealistic in this paper to attempt a complete review of all possible requirements. It may be appropriate to begin however with a brief look at the reasonably broad picture sketched in Table 1 to establish a general perspective for a subsequent more detailed discussion of the special problems of modelling sea conditions.

Attention must here be confined to a few of the more significant points about the overall picture shown in the Table with emphasis on problems which seem most important in the light of current experience and likely future trends. As already noted an obvious common feature of most of the structures concerned is that they are designed for operation at fixed stations. This does not of course mean that they cannot be tested in towing tanks and indeed there are some experiments such as those relating to tow out operations or requiring simulated current where a towing capability is useful. There are also many cases where fixed station structures basically best suited for testing in seakeeping basins are in fact tested in towing tanks for reasons such as availablity, water depths or range of wavemaking capability. In general however it seems wasteful to use a towing tank for an experiment which occupies only a small part of its length and uses the carriage only as a stationary access platform. There are moreover types of experiment which cannot be accommodated in towing tanks due to requirements such as greater width or directional waves. This applies for example in the case of moored structures with a wide spread of anchoring, tanker loading systems calling for tests in crossing seas and with particular force to some wave energy devices which together with their mooring systems can occupy an extensive plan area and need to be tested in relatively sophisticated directional waves.

The use of alternative facilities can also involve problems however. In the case of moored structures for instance it is generally important to model the depth correctly and the water depth available will thus often determine the scale of the experiment. This can cause difficulties either if it is too small for reliablity of measurement or too large for the corresponding range of wave heights which can be generated. In view of the major trend towards operation in much deeper waters, underlined by the extent of current development work on new types of structure for this purpose, there is likely to be an increasing demand for wave basins of relatively large depth. The need to test structures in extreme conditions is however also important and if as is often the case the waves are then significantly affected by the bottom it may be necessary to restrict water depth to a scale determined by the maximum height of wave which can be generated.

To accommodate these sometimes conflicting requirements there is in fact a need for wave basins in which the water depth can be widely varied up to quite large values. This is an exacting specification since it means that either a large area of bottom or the complete wavemaker and beach assemblies must be adjustable. In such a basin moreover additional features such as the capability for modelling multidirectional waves, currents or wind effects may also be needed. The cost for such installations is of course very high but the importance of ocean engineering is surely great enough to justify substantial investment in purpose built facilities of this kind.

Before leaving this brief general review of requirements to discuss in more detail the problems of modelling sea conditions, it must be emphasised that even the best equipped laboratory cannot remove the need for larger scale testing in the real environment and field measurements to check the validity of model experiments. Particular attention should in fact be drawn to the severe scaling problems which effectively invalidate model scale wave load experiments on structures such as jackets composed of relatively small diameter members subject to relatively large 'Reynolds dependent' drag forces (the term drag is here usd to denote velocity dependent components of oscillatory bluff body force and should not be confused with its usage by naval architects for steady force which may be more familiar to the ITTC). The trouble is that drag forces on full scale structures are nearly always in the so-called postcritical regime of Reynold's number whereas on model scale they are nearly always limited to the subcritical regime in which drag coefficients may be roughly double the corresponding full scale values.

Even in the largest wave tank which can realistically be contemplated, it is not possible to cross this scaling barrier for tests on whole jackets or similar complete structures except by artificial means such as adjustment of diameters to compensate for the estimated differences in drag coefficient. The author has calculated in fact that even at a scale of 1:10 or greater it is not possible to achieve even roughly valid modelling of the drag forces on both the bracings and legs of a jacket. It is possible however for relatively large individual components to measure drag at reasonably high Reynolds numbers if very high waves can be generated.

The basis for this assessment may be explained by referring to Figure 1 (derived from Reference 2). Here the so called 'scaling barrier' denoting a Reynolds number range below which modelling of drag forces will be grossly in error is set at a commonly assumed level of $10^6$. There are indications from recent research that for vertical cylinders a much lower value might be accepted and thus it may be possible for the legs to be adequately modelled. Unfortunately however $10^6$ is still considered appropriate for horizontal cylinders and it may be seen that there is thus no possibility for adequate modelling of the drag forces on the bracing members which make a major contribution to the total forces and moments on a jacket structure. This emphasises that the difficulty of obtaining reliable full scale drag data is a serious problem representing a major research requirement for testing at high Reynolds numbers in correspondingly very high waves.

## 3. MODELLING OF SEA CONDITIONS

The problems of modelling sea conditions may conveniently be discussed under 2 main headings, the first concerned with data on actual sea states and the second with wavemaking in tanks. Neither of these topics is new to the ITTC but the intention is to review recent developments with emphasis on the special requirements of ocean engineering.

### 3.1 Data on Sea Conditions

The interest of ocean engineers and indeed naval architects in general in knowledge of sea conditions is very wide and there is an extensive literature on the subject. A broad review of requirements for both design and operational purposes and of the availability of data on a range of relevant environmental parameters such as winds, currents and icing as well as waves may be found for example in Reference (3). For ITTC purposes however, the main focus of interest must be on information needed for modelling sea conditions in tanks and advising on specific wave spectrum formulae appropriate for model experiments representative of particular values of Beaufort number or Sea State Code. The Seakeeping Committee has long been concerned with these questions and a statement of its recommendations regarding spectra may be found in the Proceedings of the 13th ITTC (Reference 4).

The full details of these recommendations need not be repeated here but it may be convenient to recapitulate the salient points as a starting point for the discussion of ocean engineering requirements. The spectrum has a so-called Pierson Moskowitz form, namely:-

$$S(\omega) = \frac{A}{\omega^5} \ell^{-B/\omega^4}$$

where $\omega$ = circular frequency in radians/second. It may be entered by significant wave height alone, by significant wave height and average period or if only wind speed is known by use of a prescribed relation between wind speed and significant wave height. The relevant formulae are

$A = 8.1 \times 10^{-3} g^2$

$g$ = acceleration due to gravity

$B = 3.11 \times 10^4/\zeta_{\frac{1}{3}}^2$ in c.g.s units

$\zeta_{\frac{1}{3}}$ = significant wave height in metres

$T_1^4/\zeta_{\frac{1}{3}}^2 = A/173$

$T_1$ = average wave period ($= 2\pi\, m_o/m_1$ in usual notation) seconds.

The relation between wind speed and significant wave height is specified by the following numerical correspondence:

| Wind Speed Knots | Significant Wave Height Feet |
|---|---|
| 20 | 10.0 |
| 30 | 17.2 |
| 40 | 26.5 |
| 50 | 36.6 |
| 60 | 48.0 |

If a two-dimensional spectrum is needed, the spreading function recommended for application to the above one-dimensional spectrum is defined by:

$$S(\omega, \mu) = k \, \mathrm{Cos}^n \mu \; . \; S(\omega) \quad \frac{\pi}{2} < \mu < \frac{\pi}{2}$$

$$\text{with } n = 2 \text{ and } k = 2/\pi$$

The foregoing prescription was presented in 1972 (Reference 4) as an 'interim standard' ITTC spectrum and the Seakeeping Committee has recommended that it should be kept under review. It may therefore be useful to refer briefly to some particular aspects of ocean engineering which may call for some reassessment.

A key point already noted is that most of the structures concerned are designed to operate at fixed stations and data on sea conditions will therefore be 'site specific' and it should be added that many of the sites in question are in sea areas of limited fetch rather than in the deep ocean. This raises a number of points of some significance regarding the ITTC recommendations. The first is whether an alternative narrower spectrum might be more representative than the Pierson Moskowitz form for limited fetch areas. The JONSWAP spectrum for example (Reference 5) contains a fetch parameter and is commonly used for modelling the relatively narrow spectra typical of conditions in the North Sea and useful information about parameterisation for engineering applications may be found in References 3 and 6. Mention may also be made of Ochi's work (Reference 7) on 6 parameter fitting of measured spectra to derive 'spectral families' representative of given sea areas.

In assessing these possibilities it must be borne in mind that some types of ocean engineering experiment can be quite sensitive to details of spectral shape. Forces on the base of a gravity platform for example are most strongly influenced by the deeply penetrating long wave components and are thus sensitive to the steepness of the low frequency 'face' of the spectrum. This point is particularly significant for the study of extreme conditions which are often specified by reference to the concept of the so-called 'Design Wave' defining an individual wave crest of extreme height (see for example Reference 8) rather than in spectral terms. There is thus an important requirement for data on extreme waves at particular stations and for comparative evaluation of 'design wave' and spectral approaches to modelling them (see for example Reference 9).

Another important aspect of fixed station data concerns the relation between wave height and wind speed. The above tabular relation recommended by ITTC accords well with mean lines fitted to measured statistics for open ocean areas such as the data for 'Station India' in the North Atlantic shown in Fig. 1 (taken from Reference (10)), and was presumably derived on this basis. Corresponding statistics from stations in areas with restricted fetch such as the North Sea (see Reference 11) however show that though the mean curves are mostly very similar in form at widely differing locations, there are significant 'site dependant' shifts of general level, indicative of differences in the level of swell prevailing. This point is most apparent at low wind speeds and was brought sharply into focus by the experience of Hovercraft operators who quickly recognised that the Station India data of Fig. 2 showing a mean significant wave height of about 6 feet at zero wind speed was unrealistic for near shore areas plied by Hovercraft.

The results plotted in Fig. 3 offer a basis for making 'site specific' estimates of the wave height wind speed relation which for some fixed stations in limited fetch areas may be preferable to the ITTC recommendations. They were derived by the present author from data in References 10 and 11 as part of his work on the development of statistical methods for synthesising wave climate data. This work is being reported in more detail elsewhere. For the present it will merely be noted that good estimates of the relation between mean measured significant height and wind speed may be derived from

$$H_s = (H_1^2 + H_2^2)^{1/2}$$

where $H_1 = aW^n$ is a measure of the average height of wind sea

a and n are empirical coefficients

$H_2$ is a measure of the average height of swell

Table 2 shows a summary of values of the coefficients a, n and $H_2$ derived from the measured data in References 10 and 11. More data are needed before firm recommendations can be made but already trends may be discerned which offer a basis for engineering estimates. In particular it is apparent that a distinction should be made between sites such as India and Sevenstones fully exposed to Atlantic swell and the other more sheltered stations, particularly regarding the choice of $H_2$.

The question of the directional properties of waves is also important in some areas of ocean engineering and the interim ITTC recommendations for use of a $\cos^2\mu$ form of spreading function may need to be reassessed in response both to increasing demand for more sophisticated modelling and to recent developments in knowledge of directional seas. Some of the increasing interest in directional properties of waves has arisen because of concern about their significance in affecting the loading and corresponding fatigue life of jacket structures (see for example Reference 12). This may not be of great importance to ITTC because as already noted forces on jacket structures cannot readily be determined from model experiments.

More important from an ITTC point of view are requirements such as those relating to tanker loading systems and wave energy devices calling for model experiments in directional seas and in some cases simulation of associated winds and currents. In both cases it will often be necessary to model conditions involving crossing of seas and swells and for this purpose the foregoing formulae offer a useful basis for estimating typical relations between average heights of sea and swell and wind speed. Regarding tanker loading systems such crossing sea conditions are commonly modelled by the combination of 2 unidirectional wave trains at 2 different angles. Concerning wave energy devices, these are still in a relatively early stage of development but already the importance of the need for testing in multidirectional seas is evident.

It is fortunate therefore that in recent years there has been an increase in knowledge about directional spectra emerging from investigations such as the 'Joint North Sea Wave Project (JONSWAP - see Reference 5)' and the work of Mitsuyasu (Reference 13). In particular, Mitsuyasu's work, based on measurements of directional spectra using a 'cloverleaf' buoy (Reference 15), indicates a systematic relation between directional spread and frequency, wind speed and fetch expressible in terms of empirical formulae, details of which may be found in the Reference. Though Mitsuyasu derived these formulae from only 5 measured spectra they appear to be in reasonable accord with JONSWAP experience and have achieved quite a wide currency as a basis for parametric 'modelling' of directional spectra. The ITTC will no doubt wish to investigate the situation in some depth before drafting any revised recommendations. It may be useful however to cite here the key formulae. For simplicity a notation based on that used by Mitsuyasu will be adapted thus:

For a directional spectrum

$$E(f\theta) = G(s)\mathrm{Cos}^{2s}\tfrac{1}{2}(\theta-\theta_o).E(f)$$

G(s) is a normalising function

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

$$s = 11.5\, f_1^{-2.5} \qquad f_1 > f_{1m}$$

$$s = 11.5\, f_{1m}^{-7.5} f_1^{5} \qquad f_1 < f_{1m}$$

$$f_1 = \frac{2\pi U}{g} f$$

$$f_{1m} = \frac{2\pi U}{g} f_m$$

$f$ = wave frequency in $H_z$
$f_m$ = modal frequency in $H_z$
$U$ = wind speed

## 3.2 Wave Generation in Tanks

There are many different methods for generating waves in tanks including use of wedges, flaps, pistons, cams and pneumatic devices and References 16 and 17 for example may be cited as useful sources of information on basic principles. The present concern is with techniques for meeting the special requirements of ocean engineering identified in the previous sections, relating to unidirectional modelling of specified spectra and extreme 'Design Wave' conditions and generation of multidirectional waves to simulate crossing seas and directional spectra.

### 3.2.1 Unidirectional spectra

When modelling spectra for ocean engineering experiments it is important to consider not only their shape but also the periodicity of the resulting waves at fixed points in the tank. It is generally necessary in fact to ensure that reasonably long return periods can be achieved especially for experiments such as those involving mooring or dynamic positioning systems with very low response frequencies. This requirement means that harmonic synthesisers generating line spectra with equally spaced frequency components commonly used for ship model testing (see for example Reference 18) are not acceptable, because the resulting waves though not periodic as encountered by a moving model have very short maximum return periods at fixed points. For a spectrum with lines spaced at frequency intervals, $\delta f$ $H_z$, the maximum return period at a fixed point is in fact $^1/\delta f$.

An effective technique for generating irregular waves corresponding to specified spectral shapes but with very long maximum return periods, is the so called 'filtered noise' method of control function synthesis developed by the UK Hydraulics Research Station (Reference 19). A control synthesiser using this system has in fact now been installed at the NMI, superseding the 16 component harmonic synthesiser (Reference 20) previously used. Details of the system may be found in Reference 19. For the present it must suffice to say that it involves the generation of random noise by a digital ('shift register') technique which is passed through a shaping filter to impose the required spectral form and then translated into a suitable analog control signal. Maximum return periods ranging up to very high values can be selected by suitable setting of the shift register controls.

### 3.2.2 Extreme waves

Attention has been drawn in previous sections to the importance of being able to generate very large individual waves both from the point of view of achieving high Reynolds numbers for scaling purposes and for the testing of structures in extreme 'Design Wave' conditions. There are a number of different ways in which this can be done by suitable control of the input signal to conventional wavemakers, using the dispersive property of the waves to arrange very high concentrations of energy at particular points in space and time. Another possibility is to use a travelling flap fitted to the carriage and towed far enough to generate a suitable train of large waves, but stopping short of the structure under test. A wavemaker using this principle, assigned the name 'Wavedozer', has been developed at the National Maritime Institute (see Reference 21) and has proved to be a relatively cheap and simple way of generating very large waves for fixed station testing in a conventional towing tank.

There is not space here to describe all the possibilities indicated above in detail but some brief further comments on some of the specific techniques concerned may be helpful. Considering first the use of conventional wavemakers with appropriate control signals, reference may be made to 3 different approaches. The first involves use of a spectral input specified in such a way as to ensure that the frequency component wave trains for all the frequencies covered, all come into phase at some chosen point of space and time. Unfortunately the 'filtered random noise' type of spectral synthesiser is not suitable for this technique because the phase relationships of the frequency components are not readily controlled. A harmonic synthesiser with phase control of the frequency components as previously employed at NMI however, is highly effective for this purpose. The phase settings required to achieve complete phase coincidence at a distance $x_o$ from the Wavemaker may in fact then be determined as follows:

Let the surface elevation history $\eta(x_o t)$ be expressed in the form:

$$\eta(x_o t) = \sum_n F(\sigma_n) A_n \text{ Cos } (k_n x_o - \sigma_n t + \varepsilon_n + \delta_n)$$

Where $F(\sigma_n)$ is the amplitude calibration function for the wavemaker concerned:

$A_n$ is the amplitude setting for frequency $\sigma_n$

$k_n$ is the wave number $= \sigma_n^2/g$ according to linear theory for deep water

$\varepsilon_n$ is the phase setting for frequency $\sigma_n$

$\delta_n$ is the phase difference between the control signal and the wave elevation at some datum position $x = o$.

To achieve phase coincidence of the waves at $x = x_o$, the setting $\varepsilon_n$ should be chosen such that:

$$\varepsilon_n = 2m\pi - k_n x_o - \delta_n$$

where m is an integer chosen so that

$$0 < \varepsilon_n < 2\pi.$$

In some cases, spectral input may not be available and there are many wavemakers which normally run at fixed stroke settings but have provision for controlled variation of frequency. There are 2 possible techniques which may be mentioned for making locally large waves in such cases. The first is to arrange for successive packets of energy to be input at decreasing frequencies with correspondingly increasing group velocities, such that they all converge at some chosen distance from the wavemaker. In deep water, the group velocity $C_g = \frac{1}{2}g/\sigma$ and the conditions for convergence of energy at $x = x_o$ may be specified as follows.

For an energy packet leaving the wavemaker at time $t = o$ with frequency $\sigma_o$ to reach $x_o$ at the same time as a packet leaving at a time $t = \delta t$ with frequency $\sigma_o + \delta\sigma$, the requirement is:

$$\frac{2x_o}{g}\sigma_o = t + \frac{2x_o}{g}(\sigma_o + \delta\sigma)$$

$$\text{or} \quad \frac{\delta\sigma}{\delta t} = \frac{g}{2x_o}$$

In the limit for a continuously varied frequency, this relation may be integrated to define frequency as a function of time thus:

$$\sigma(t) = \sigma_o - \frac{g\,t}{2x_o}$$

A second technique applicable to conventional fixed stroke wavemakers is to use the so called 'Benjamin Feir' instability phenomenon (Reference 22) which leads to progressive break up of nominally regular wave trains into heavily modulated groups with locally high peaks of amplitude when prescribed limits of steepness are exceeded. These limits though theoretically defined in the reference must in practice be determined by experiment.

Regarding the less conventional 'Wavedozer' technique a detailed account of the operation of the prototype developed at NMI may be found in Reference 21 and need not be repeated here. It may be of interest to mention however that a more permanent installation with a retractable flap has now been fitted and successfully operated, generating waves up to 0.95 m high.

### 3.2.3 Multidirectional waves

There are various ways of generating directional waves. The so called 'Snake' wavemaker developed at the NSMB in Wageningen (Reference-23) is a well known example. It comprises lines of articulated flaps all driven at the same frequency along 2 sides of a rectangular tank. It has been shown by the present author (Reference 24) that by suitable superposition of the phase setting sequences it can generate multidirectional waves at any given frequency. It cannot however model a given directional spectrum because of the lack of mixed frequency capability. More recently an alternative system has been developed at the UK Hydraulic Research Station (Reference 25) consisting of an arc of flaps all generating one dimensional spectra along different axes focussed to produce a required directional spectrum within a central working area of a square basin. This has proved effective for many types of ocean engineering experiment but the relatively restricted area of validity of the directional spectrum is a serious limitation for testing structures such as wave energy devices requiring a large plan area.

The capability for generating given directional spectra valid over a wide area can be provided in fact by an extension of the 'Wageningen Snake' concept to mixed frequency operation which is simple in principle but involves the practical complication of a separate control signal for each flap. The principle may be explained by reference to Figs. 4 and 5. Fig. 4 shows diagrammatically how each 'cell' of the frequency-direction plane on which a directional energy spectrum is plotted corresponds to a component regular wave train and Fig. 5 illustrates the profile at time t of the flap displacement along a snake required to generate that component. Each individual flap is here oscillating as in the case of the NSMB 'Snake' with the same amplitude and frequency but with a phase setting such that the profile travels along the snake at speed $c\mathrm{Sec}\theta$ where c is the phase speed of the waves normal to their crests. To generate a complete spectrum the control signal $S_r$ for each flap must be the sum of the components corresponding to each frequency $f_n$ and direction $\theta_m$ and may be written as:

$$S_r = \sum_{n}\sum_{m} T_n a_{nm} \mathrm{Cos}(k_n \mathrm{Sin}\theta_m x_r - 2\pi f_n t)$$

where $T_n$ is the transfer function relating signal amplitude and wave amplitude.

A 'Mixed Frequency Snake' of the type described above has recently been installed in a new tank built at Edinburgh University specially for work on wave energy devices, and this is certainly a most effective technique if given directional spectra valid over a wide area are required. In some cases however less sophicated directional patterns may suffice and the possibility of adapting an existing unidirectional facility to provide a simpler but more limited capability may be attractive. The present author has in fact explored a number of such possibilities and demonstrated their effectiveness by small scale experiments and it may be of some interest to report here briefly on the most promising of the techniques investigated.

The aim was to devise simple passive hardware for converting the unidirectional waves in a conventional towing tank into multidirectional waves. The problem thus concerns a long and relatively narrow tank and in such a tank any pattern of free waves can only contain a limited number of discrete directional modes because of the requirement for antinodes at the wall. It was quickly recognised that the key to any solution must thus lie in ways of promoting the development of these discrete free modes.

Considering for simplicity only the symmetrical modes, at a single frequency, these consist of pairs of oblique wave trains as illustrated in Fig. 6(a) and the surface elevation according to linear theory is defined by the equation:

$$\eta(x,y,t) = 2a_n \mathrm{Cos}(k\mathrm{Sin}\theta_n y)\ \mathrm{Cos}(k\mathrm{Cos}\theta_n x - \sigma t)$$

with the requirement to satisfy the wall conditions that:

$$k\mathrm{Sin}\theta_n = 2\pi n/b.$$

The transverse wave profile at any station is a standing wave with antinodes at the wall and an amplitude distribution proportional to $\mathrm{Cos}(k\mathrm{Sin}\theta_n y)$ as indicated by the hatching in the figure.

If the original unidirectional wave train is described by:

$$\eta_o(x,y,t) = A_o\ \mathrm{Cos}\ (kx - \sigma t)$$

it is difficult to imagine any passive hardware which can induce the half cycle phase changes necessary to establish the negative lobes of amplitude which characterise any oblique mode. The difficulty disappears however if it is accepted that the required multidirectional pattern must contain some remnant of the original transverse wave train superposed on the oblique modes. Such a pattern can be described by:

$$\eta(x,y,t) = a_o\ \mathrm{Cos}(kx - \sigma t)$$
$$+ 2a_n\ \mathrm{Cos}(k\mathrm{Sin}\theta_n y)\ \mathrm{Cos}(k\mathrm{Cos}\theta_n x - \delta t)$$

and a transverse profile defined for convenience at x = o may be written as:

$$\eta(o,y,t) = [a_o + 2a_n\ \mathrm{Cos}(k\mathrm{Sin}\theta_n y)]\ \mathrm{Cos}\sigma t$$

so that the transverse amplitude distribution has no negative lobes provided that:

$$a_o \geq 2a_n.$$

In the special case $a_o = 2a_n$, noting that

$$k \sin\theta_n = 2\pi n/b$$

$$\eta(o,y,t) = a_o\,[1 + \cos(2\pi ny/b)]\cos\sigma t$$

so that the amplitude distribution is as shown hatched in Fig.-6(b) and there are node points at $y = \pm b/2n$.

These node points are in fact key features since if they can be at least approximately established by insertion of suitable fixed obstacles it may be expected that the required pattern will tend to develop, and this has in fact been demonstrated by experiments in a small tank at Feltham. Various types of obstacle were tested and the use of masks fitted to the face of the wavemaker was also tried. Wavemaker masks and triangular obstacles were the most effective but the former are considered to invlove some risk of damage to the wavemaker. Attention has therefore been concentrated on the use of triangular obstacles.

Fig. 7(a) illustrates the concept and Fig. 7(b) shows a multidirectional pattern generated in a small tank (15 m long x 1.2 m wide x 1.2 m deep) using 2 triangular obstacles centred at $y = \pm b/4$. Decisions regarding the possibility of installing such a system in the main towing tank (No.3) at Feltham (400 m long x 16 m wide x 8 m deep) depend at the time of writing on the extent and significance of demand for a multidirectional capability of this type. Meanwhile Fig. 8 has been drawn to indicate what the range of this capability would be. The heavy curves define for the working range of wave period (or length) the directions of the discrete symmetrical oblique modes corresponding to deployment of n obstacles at the appropriate nodal points.

In assessing this capability it must be emphasised that it is intended mainly for use at constant frequency for investigations requiring relatively simple multidirectional patterns. It is considered in fact to be particularly suitable for use in testing wave energy devices, having the significant advantage in this case that the crest length which is often an important parameter in such work is very precisely determined.

It can also be used for a mixed frequency spectrum but the resulting waves will be unrealistic. This is because for any given obstacle spacing the spread angle must follow the corresponding discrete line in Fig. 8 and hence must increase with increasing period and this is contrary to the trends occurring in nature.

Before leaving this section on modelling of multidirectional waves it should be emphasised that the usefulness of experiments in such conditions depends on a corresponding ability to measure and analyse the waves generated. Unfortunately there is not enough space here to include a discussion of this important topic and it must suffice to draw attention to some references where detailed information may be found. Reference-26 is a review paper covering a wide range of methods for measuring and analysising directional spectra and Reference 27 is an assessment of various probe array geometries using a recently developed 'maximum likelihood method' of analysis involving an optimised 'data adaptive' filtering function. Reference 24 relates to the NSMB Snake and Reference 25 to the HRS system already discussed and both are relevant to directional spectra in general. Regarding the passive obstacle technique being developed at NMI no detailed measurements and analysis have been undertaken at the time of writing. Some thought has been given to the problems however and when operating at constant frequency it is expected that a relatively small number of probes should suffice to determine the amplitudes of the component modes. It is worth noting moreover that the wave profile along the wall if photographed at any instant contains all the information needed to determine the amplitudes of all the modes (assuming linearity) since the 'signature' of each component wave train will be a sine wave with length = $2\pi/k \sin\theta_m$.

## CONCLUDING REMARKS

This review began with with a general discussion of the implications for ITTC of the rapidly expanding ocean engineering activity regarding both Technical Committee mandates and availability of suitable testing facilities. Emphasis was placed on the wide range of technical expertise now required no longer confined to the traditional naval architecture headings of the existing Committees and it was suggested that a new Committee may be needed to cover ocean engineering topics.

In discussing the availability of facilities particular attention was drawn to the major new requirements for fixed station testing covering a wide range of duties of water depths and sea conditions and the problems of meeting these in existing towing tanks, seakeeping basins and wave flumes, including difficulties in scaling of wave loads on some types of structure. It was suggested that the importance of these new requirements might call for the building of some new facilities purpose built for ocean engineering experiments.

Attention was then turned to the specific problems of modelling sea conditions for ocean engineering purposes with which the author has been particularly concerned, including both questions relating to data on sea conditions as well as methods of generating waves in tanks.

Regarding sea data, the ITTC recommendations for an 'interim standard spectrum' were discussed in the context of the special requirements for offshore structures deployed at fixed stations often in areas of limited fetch. It was suggested that reassessment of the recommendations may be needed including the possibility of other options for spectral form, wave height and wind speed relation and assumptions regarding directional spread. The need for guidance on specifications of extreme conditions including both spectra and 'design wave' modelling was also noted.

The discussion of wave generation in tanks covered unidirectional waves, including both spectra and extreme individual waves, as well as multidirectional waves. In considering unidirectional waves attention was drawn to the importance of correct modelling of long return periods at fixed points which tends to exclude the use of harmonic synthesisers for generating the control signals for the spectra, and to favour the alternative technique of using 'filtered random noise'

A number of different techniques for generating multidirectional waves was discussed and it was suggested that a 'mixed frequency' extension of the NSMB 'Snake' concept is most suitable for experiments requiring modelling of given directional spectra valid over a large plan area. For cases where simpler modelling is acceptable, a technique of adapting existing unidirectional facilities to provide a limited multidirectional capability by insertion of obstacles, which has been developed at the NMI, was described.

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## TABLE 1

## THE SCOPE OF OCEAN ENGINEERING REQUIREMENTS

A Checklist of Structure types, Facility Parameters, and types of Experiment (not claimed to be complete).

### a) STRUCTURE TYPES

Cable/Pipelay Barges
Compliant Towers
Dredging Systems for Seabed Mineral Recovery
Drillships
Gravity Platforms
Guyed Towers
Jacket Structures
Jackup Platforms
Offshore Islands for Nuclear Power Stations
Pollution Control Systems
Semisubmersibles
Single Point Moorings
Tanker Loading Systems
Tethered Buoyant Platforms
Thermal Energy Devices
Wave Calming Devices
Wave Power Devices

### b) FACILITY PARAMETERS

| Facility | Parameters |
|---|---|
| Tanks | Plan area<br>Water depth<br>Wavemaking capability<br>Towing capability<br>Access arrangements<br>Current simulation<br>Wind simulation |
| Cavitation tunnels | Working section dimensions<br>Maximum flow speed<br>Pressure range |
| Circulating water channels | Working section dimensions<br>Maximum flow speed |
| Wind tunnels | Working section dimensions<br>Range of flow speeds<br>Pressure range<br>Simulation of profile and turbulence of natural winds |

## TABLE 2

## WAVE HEIGHT WIND SPEED CORRELATION

Summary of results of analysis of data from References 10 and 11 (see Figure 3)

| STATION | $a$ | $n$ | $\sigma$ feet | $a_m$ | $n_m$ | $\sigma_m$ feet | $H_2$ feet |
|---|---|---|---|---|---|---|---|
| India<br>($59^\circ$N $19^\circ$W) | 0.14 | 1.41 | 1.53 | 0.11 | 1.46 | 2.28 | 6.5 |
| Sevenstones<br>($50^\circ 4'$ $6^\circ 4'$W) | 0.12 | 1.43 | 0.88 | 0.11 | 1.46 | 0.98 | 4.2 |
| Shambles<br>($50^\circ 31'$N $2^\circ 20'$W) | 0.08 | 1.32 | 0.60 | 0.076 | 1.38 | 0.69 | 1.5 |
| Owers<br>($50^\circ 37'$N $0^\circ 41'$W) | 0.19 | 1.18 | 0.50 | 0.076 | 1.38 | 1.57 | 2.1 |
| Varne<br>($50^\circ 56'$N $1^\circ 17'$E) | 0.084 | 1.38 | 0.34 | 0.076 | 1.38 | 0.62 | 1.4 |
| Mersey Bar<br>($53^\circ 31'$N $3^\circ 20'$W) | 0.015 | 1.84 | 0.65 | 0.076 | 1.38 | 0.95 | 1.8 |

$H_s = (H_1^2 + H_2^2)^{\frac{1}{2}}$ is significant in feet

$H_1 = aW^n$ is height of sea in feet

$W$ = Wind speed in knots (corrected to 10m height)

$H_2$ = Mean measured $H_s$ at lowest wind speed is estimated mean height of swell

$\sigma$ = Root mean square deviation from mean measured $H_s$

$a_m$, $n_m$, $\sigma_m$ are the corresponding values for a, n, and $\sigma$ derived from fitting data for more than one station.

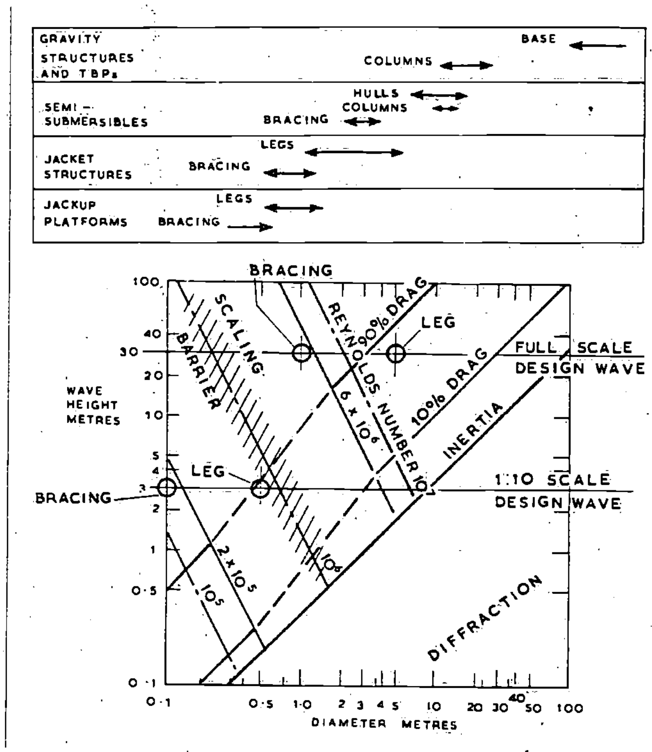


Figure 1 Scaling of Wave Loads (Based on Morison's equation for conditions near surface - reference 2)

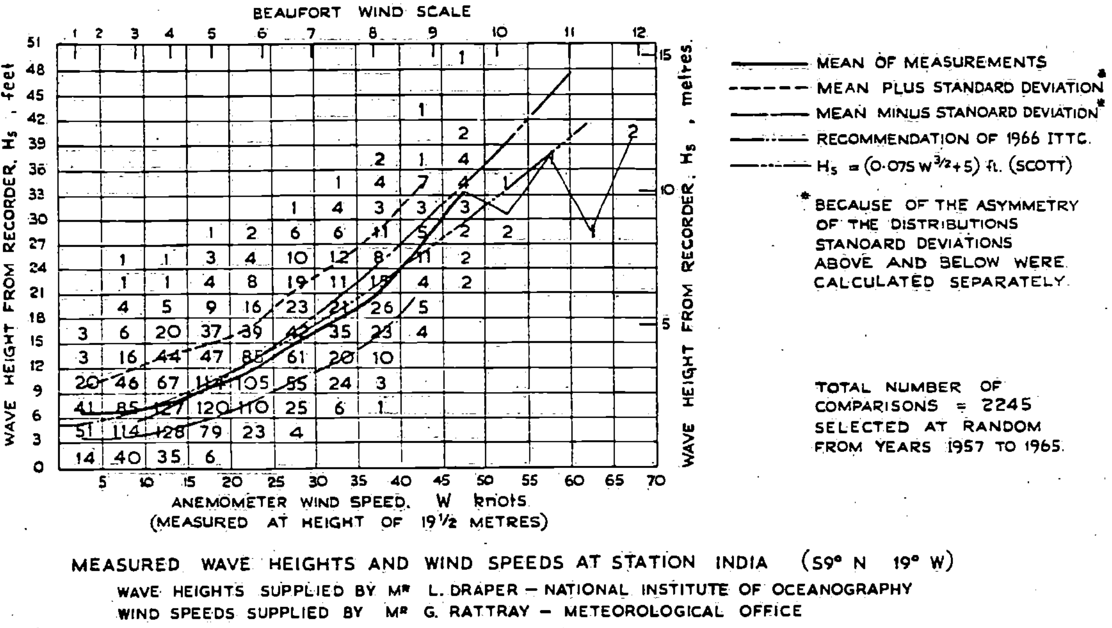


Figure 2 Measured Wave Heights and Wind Speeds at Station India (59°N 19°W) (Reference 10)

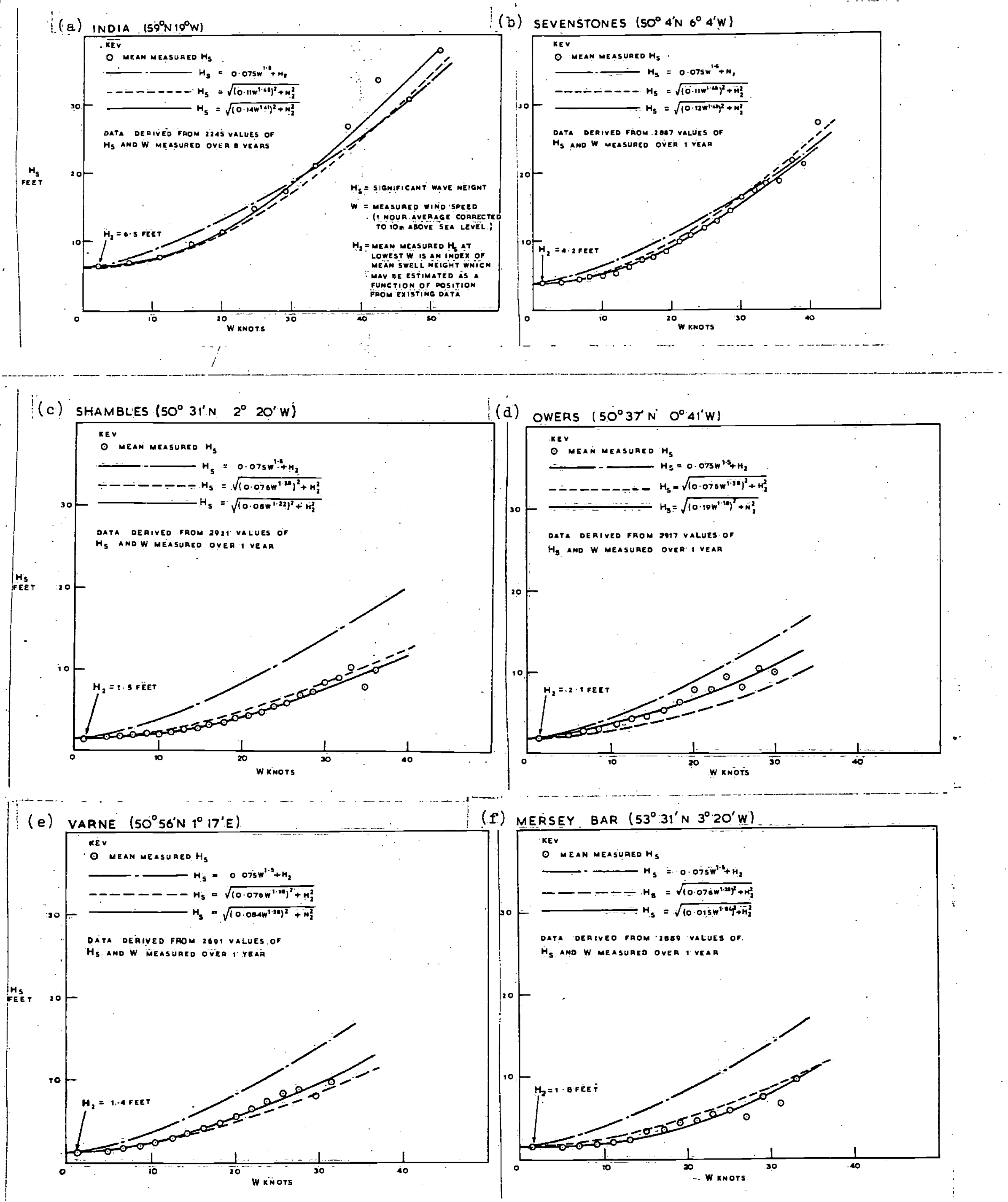


Figure 3 Fit of Various Formulae relating Mean Measured Wave Heights and Wind Speed

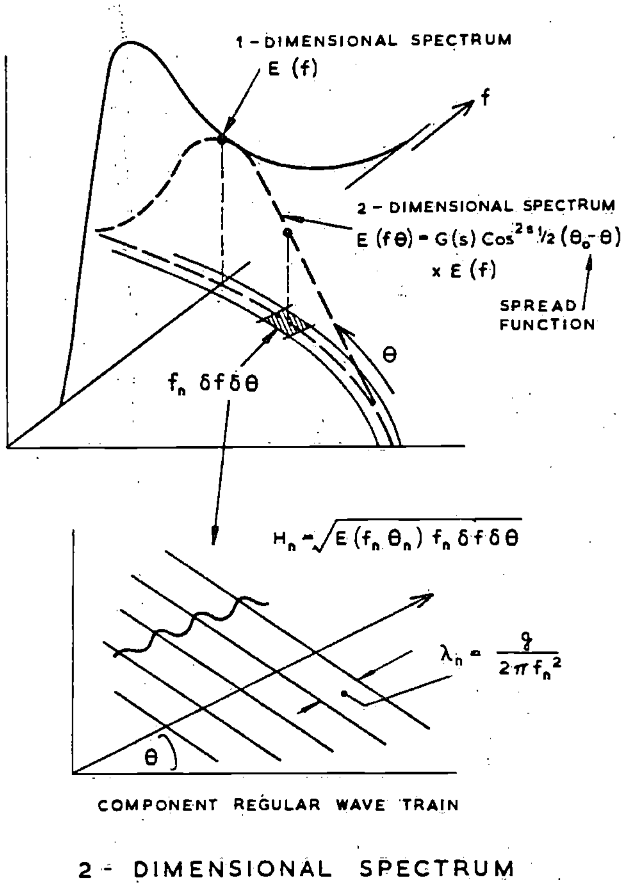


Figure 4 Modelling of a Directional Spectrum

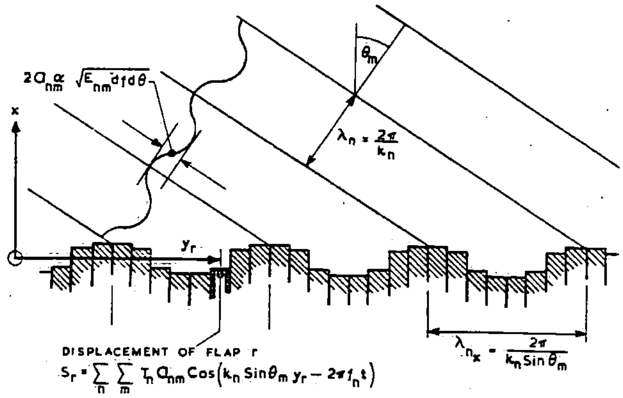


Figure 5 Generation of a Directional Spectrum: the 'Mixed Frequency Snake' Concept

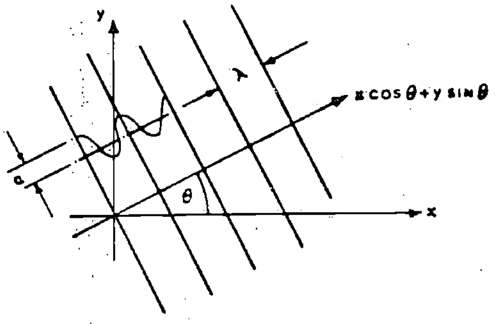
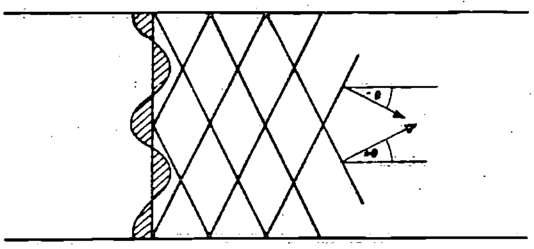
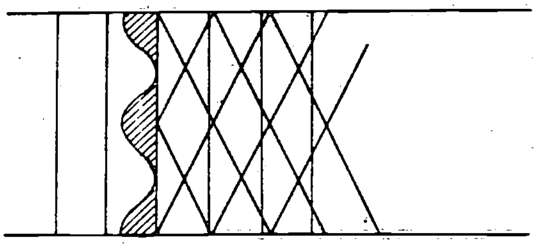


FIG. 1. REGULAR WAVE TRAIN IN OPEN WATER



(a) PAIR OF OBLIQUE WAVE TRAINS



(b) TRANSVERSE WAVES AND PAIR OF OBLIQUE WAVE TRAINS

Figure 6 Directional Modes in a Long Tank

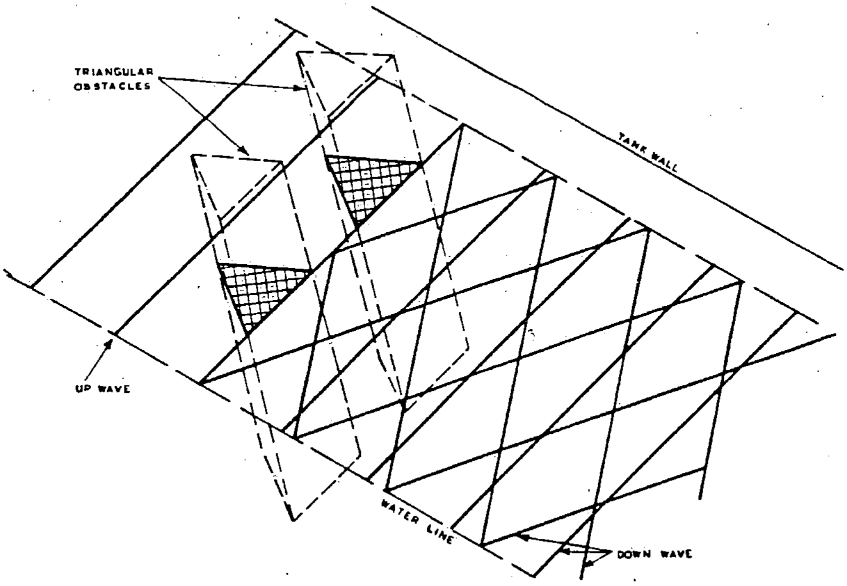
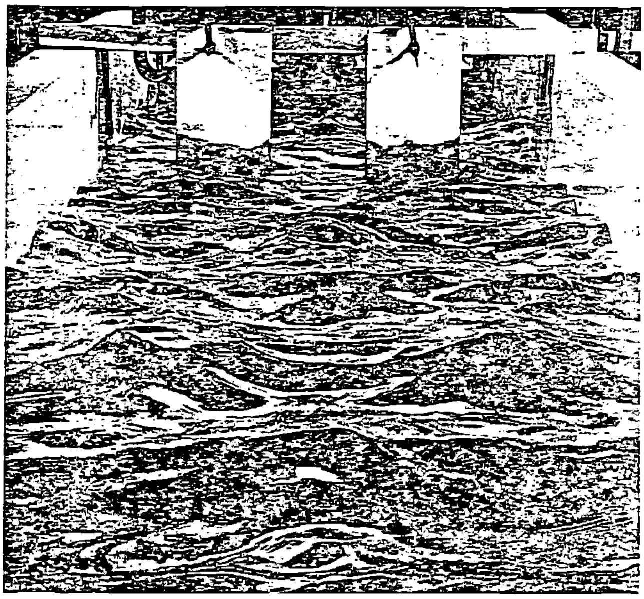
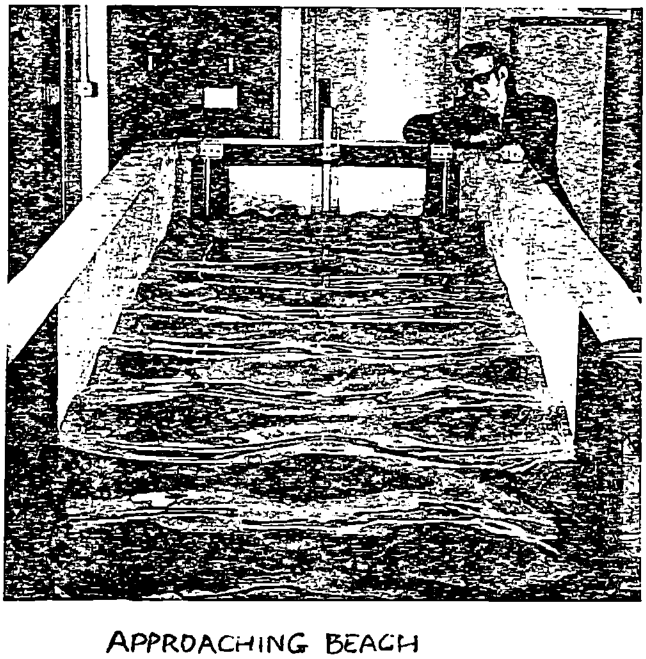


Figure 7 Directional Wave Gate

(a) Diagrammatic View



NEAR OBSTACLES



APPROACHING BEACH

Figure 7 Directional Wave Gate

(b) Photographsof Multidirectional Waves

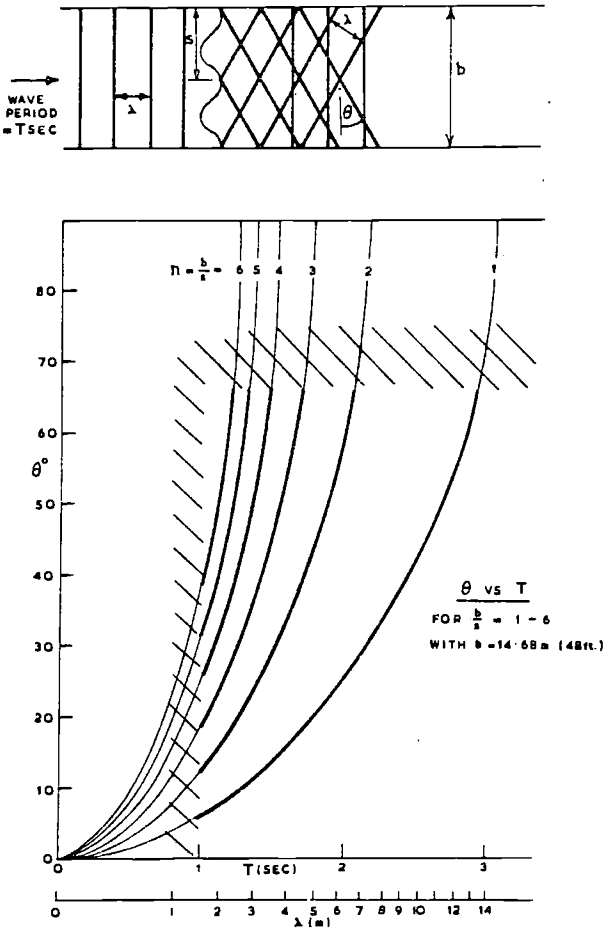


Figure 8 Relation of Direction and Period for Symmetrical Waves Modes in No. 3 Tank at the NMI Feltnam.