MOORED SHIP RESPONSE IN IRREGULAR WAVES

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ABSTRACT

The traditional concept of representing a "random" sea state by just a variance spectral density has been found to be insufficient for modelling the slow drift oscillations of large moored ships. This paper illustrates, through experimental investigations, the importance of including wave grouping as an additional design parameter. A special technique called SIWEH, developed by the Hydraulics Laboratory of the National Research Council Canada, for the generation of realistic wave climates which include wave grouping, is presented. However, when generating the grouped sea state, one also has to properly create the group-bound long wave components. The effect of proper compensation for the spurious free wave components is illustrated by the test results on the moored vessel response.

1.0 INTRODUCTION

It has been observed, in physical model studies, that the response of moored vessels, in terms of motions and mooring loads, is far greater in irregular waves than in regular waves of equivalent wave height. This is due to the non-linearities found in irregular waves which give rise to slowly varying forces which over time are able to build up large oscillations of the vessel, leading to high mooring forces.

A vessel floating in regular waves experiences a steady force, while in the case of irregular waves, since the wave height is not constant, the force will vary with the wave envelope. This results in a slowly varying force on the vessel with a period equal to that of the wave groups.

The horizontal oscillations, such as surge, sway and yaw, for a large vessel have natural periods in the range of 20 seconds to a few minutes, far greater than the wind generated waves. The largest response of the vessel would be expected to occur when the period of the groups, which is often in the low frequency range, is equal to or lies in the vicinity of these natural periods. Although considerable research work has been carried out [Remery and Hermans (1972), Rye et al (1975), Van Oortmerssen (1976), Faltinsenen and Loken (1978), Pinkster (1979), Spangenberg (1980)], to investigate these slowly varying forces, there exists no suitable technique to simulate wave groups in terms of their periodicity and energy content. Recently the Hydraulics

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Laboratory of the National Research Council Canada has developed a synthesis technique to generate realistic sea states which include wave grouping [Funke and Mansard (1980)]. This technique, which can generate varying amounts of grouping and group periods, was used in the present study in order to illustrate the importance of these slowly varying forces.

Longuet-Higgins and Stewart (1964), using the concept of radiation stress, have shown that in irregular waves, a set-down of mean water level (MWL) occurs under wave groups with a corresponding set-up between the groups. This results in a long wave variation of mean water level, with a period equal to that of the wave group in question, interacting with the vessel.

This variation of MWL, known as group-bound long wave or Bounded Long Wave, is of second order and therefore cannot be reproduced correctly with classical first order wave generation. Currently, many investigations are being carried out to establish the importance of these second order wave components in the assessment of the dynamics of structures (fixed or floating).

This paper will also illustrate, through experimental investigations, the importance of reproducing this MWL variation in order to have a realistic response of the vessel.

2.0 LOW FREQUENCY COMPONENTS IN IRREGULAR WAVES

Figure 1 presents a definition sketch of the frequency components present in irregular waves, which result in slow drift oscillations of the vessel. The Smoothed Instantaneous Wave Energy History (SIWEH) shown in this figure, serves as a useful tool to define the wave group characteristics present in a sea state. This function, developed at the National Research Council Canada [Funke and Mansard (1980)], can be computed from the water surface elevations by using the following equation:

$$E(t) = \frac{1}{T_p} \int_{\tau=-\infty}^{\infty} \eta^2(t+\tau) \cdot \phi_K(\tau) d\tau$$

where $E(t)$ = SIWEH function
$\eta(t)$ = water surface elevation
ϕ_k = smoothing window function
T_p = peak period of the spectrum

A measure of the wave group activity, known as the Groupiness Factor GF can be computed using the following expression:

$$GF = \sqrt{\frac{1}{T_n} \int_0^{T_n} (E(t)-\bar{E})^2 dt} \Big/ \bar{E} = \frac{\sqrt{m_{\varepsilon_0}}}{m_0}$$

where T_n = length of wave record
E = mean value of $E(t)$
$m_{\varepsilon 0}$ and m_0 = zeroth moments of the SIWEH and the variance spectral densities

The SIWEH describes the distribution of wave energy in the time axis while the GF represents the standard deviation of the SIWEH about its mean and normalized with respect to its mean.

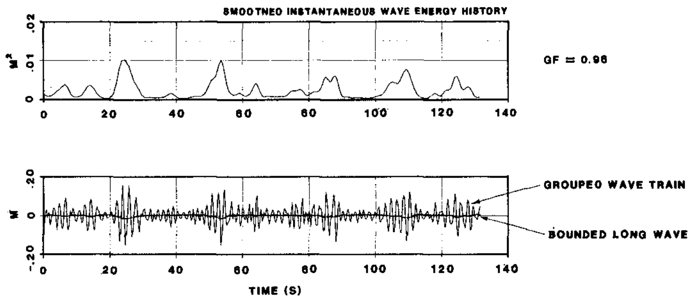


FIG.1 GROUPED WAVE TRAIN AND ITS LOW FREQUENCY COMPONENTS

Figure 1 also illustrates the long period oscillation of the MWL generated by the wave groups. This oscillation, known as Bounded Long Wave (BLW) is 180° out of phase to the SIWEH function. It can be shown that the amplitude of this oscillation is directly related to the Groupiness Factor GF.

As discussed above, the Bounded Long Wave cannot be correctly reproduced in the model by first order wave generation since the boundary condition required at the paddle to generate it cannot be satisfied directly (Ottensen-Hansen et al 1980, Bowers 1980). This results in the generation of certain spurious long wave components (shown in Figure 2), which in turn lead to a vessel response which is not realistic. The two main sources which contribute to these spurious long waves are:

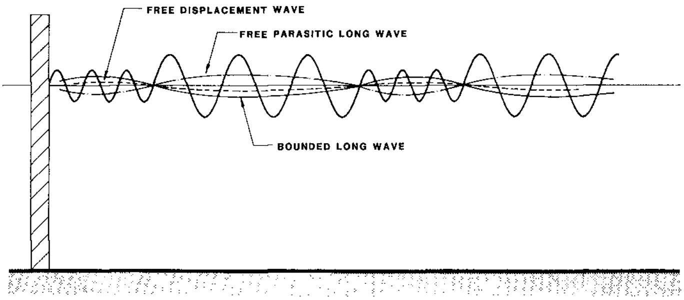


FIG.2 DEFINITION SKETCH OF LONG WAVE COMPONENTS IN A GROUPED WAVE TRAIN

1. free parasitic long wave, which is opposite in phase to the BLW, generated at the paddle since the particle motions from the group induced long waves cannot pass through the solid paddle;
2. free displacement waves generated due to the moving boundary of the paddle.

These spurious long waves are called free waves since they travel with their own celerity, while the Bounded Long Wave travels with the group velocity since it is bound to the wave groups. The free long waves can travel back and forth along the flume corrupting the incident wave system, since the reflection coefficient of these long waves is often very high (50 to 60%) even from beaches with mild slopes. However, the free long waves can be eliminated by including proper suppression terms in the wave generation. Under a cooperative program between the Danish Hydraulic Institute, the Delft Hydraulics Laboratory and the National Research Council Canada, techniques for the correct reproduction of the Bounded Long Wave were developed by verifying the various long wave terms and the effectiveness of the suppression. A joint publication by the three laboratories (Barthel et al 1983), describing the various techniques involved, is being submitted to Ocean Engineering. The present paper, therefore, only deals with the application of this technique in the assessment of the vessel response.

3.0 WAVE GENERATION TECHNIQUES

The effect of wave grouping on the dynamics of floating or fixed structures can be investigated in laboratory models by the wave synthesis technique illustrated in Figure 3. This technique, developed at the National Research Council Canada, can be used to synthesize time series with different wave grouping characteristics, keeping however the variance spectral density of the sea state constant. Because of

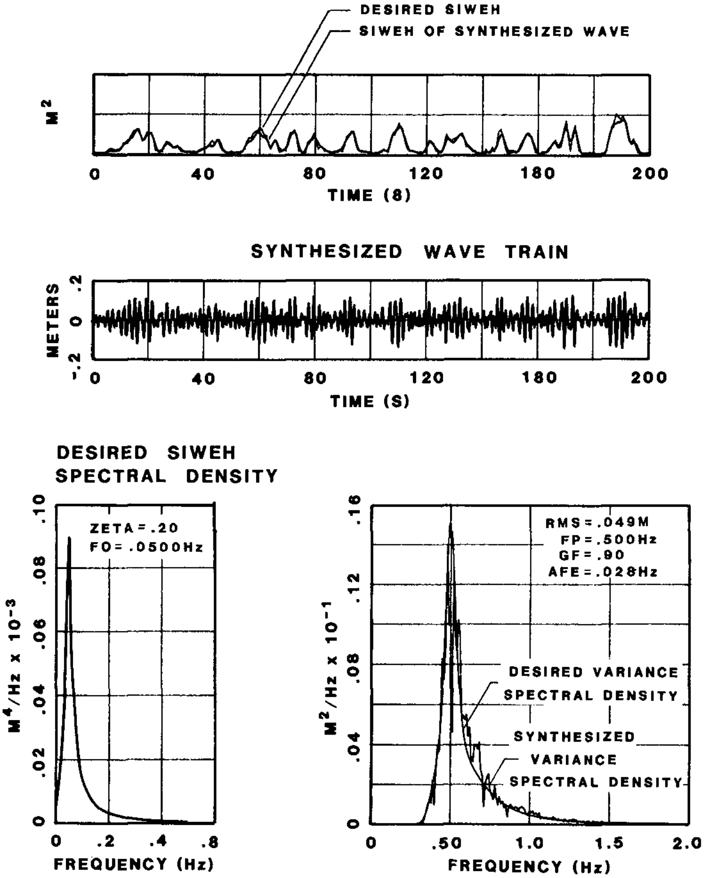


FIG.3 SYNTHESIS OF A GROUPED WAVE TRAIN

the high correlation which exists between the wave groups and the slow drift oscillations, this technique is particularly useful to evaluate their relationships in a given sea state.

In the absence of sufficient analysed prototype records of wave groups, a theoretical model of the SIWEH spectral density is used in this synthesis. The parameters of this model can effectively be varied to generate SIWEH functions having different characteristics. Since, $GF = \sqrt{m_{\varepsilon_0}}/m_0$, the area under the SIWEH spectrum, shown in Figure 3, can be varied to achieve different Groupiness Factors with the same variance spectral density. On the other hand, different period and distribution of the groups can be obtained by varying the peak frequency and the width of the spectrum.

As shown in Figure 3, the synthesized wave train satisfies the frequency domain characteristics of the desired variance spectral density as well as the time domain characteristics defined by the SIWEH function. Details of the various steps involved in this synthesis technique are well documented in Funke and Mansard (1980).

4.0 EXPERIMENTAL SET-UP

The investigations in the physical model were carried out to a scale of 1:100 using a model of a 227000 DWT tanker in a wave basin approximately 67 m long and 7.7 m wide. The flume, Figure 4, was equipped with a hydraulically-driven wave generator controlled by an on-line computer. The model tanker, located midway between the wave paddle and the beach, was moored at about a 30° angle between the bow and the incident wave direction. Greater angles could not be tested due to the relative narrowness of the flume. A mild sloped stone beach (1:25) ensured good dissipation of the incident energy.

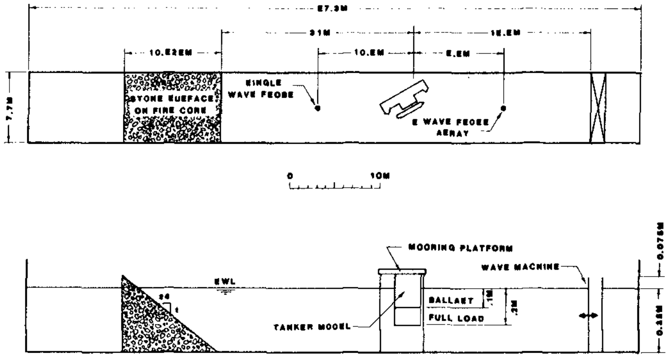


FIG.4 SHIP MOORING BASIN LAYOUT

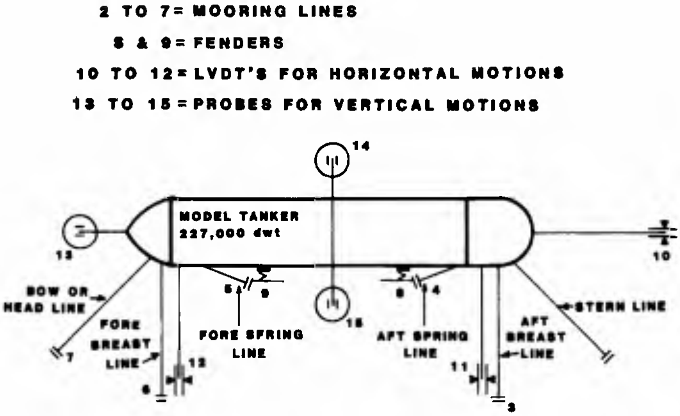


FIG.5 GENERAL LAYOUT OF MOORING CONFIGURATION

FIG.6 PHOTOGRAPH SHOWING A GENERAL VIEW OF THE PHYSICAL MODEL

The water surface elevations were monitored using twin wire capacitance probes located midway between the vessel and the wave paddle. An array of five probes was used to establish the reflection characteristics of the vessel and of the beach.

The model tanker was moored, as shown in Figures 5 and 6, by six mooring lines (representing four prototype nylon lines each with a pretension of 30 t and two steel spring lines with nylon tails with 10 t pretension). Two fenders, placed symmetrically, absorbed the impacts of the vessel on the mooring jetty. The jetty was supported on thin piles, and presented no obstruction to the waves. Since a direct measurement of the six degrees of freedom of the vessel motions (surge, sway, heave, roll, pitch and yaw) was not feasible, the approach used was to monitor the motions at the six locations (10 to 15) shown in Figure 5 and then to relate them to the six degrees of freedom. Accordingly, the vertical motions were measured by capacitance type probes while the horizontal movements were monitored by using Linear Variable Displacement Transducers (LVDT).

In model studies it is not easy to simulate the non-linear load elongation characteristics of the mooring lines by just varying their elasticity. Therefore, non-stretching mooring lines were used and the elasticity of the prototype mooring lines were simulated by the device shown in Figure 7. This simulator, developed at the Hydraulics Laboratory of the National Research Council Canada, consists of a cantilevered blade spring of rectangular cross-section mounted on a plate. The desired non-linear load-elongation characteristics of the mooring line can be achieved by varying the positions of the spring contact points so that as the spring is pulled down onto them an effective shortening of the length of the spring and consequently a stiffening effect results. Mailhot et al (1982) have recently developed a computer method for determining these contact positions.

Stainless steel is a spring material well suited for this device since it combines very low permanent deformation with high elasticity. The choice of the width and thickness of the spring can be used to vary the stiffness to a certain extent. The frequency response of this simulation was found to be high, on the order of 5 to 10 Hz.

While the elasticity of the prototype mooring line is simulated by the above device, the loads on the different lines are monitored by using Direct Current Displacement Transformers (DCDT) in a force transducer. The DCDT has a moving core, suspended from a pair of spring blades, and connected to the mooring line. As the core moves through the electromagnetic field within the DCDT windings, a voltage output is produced which is calibrated to the displacement of the core and thus to the force required to achieve that displacement.

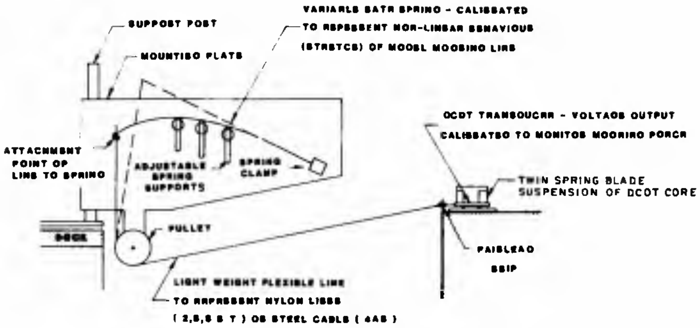


FIG.7 NON - LINEAR CANTILEVER SPRING MOORING SYSTEM

FIG.8 PHOTOGRAPH SHOWING THE CANTILEVER SPRING, FENDER, AND MOORING FORCE TRANSDUCER

5.0 EFFECT OF LONG WAVE COMPENSATION ON VESSEL RESPONSE

In order to establish the effect of the correct reproduction of the Bounded Long Wave (BLW) on vessel response, tests were carried out using two different cases of wave generation: with and without compensation for spurious long waves. The BLW components measured in these two cases are presented in Figure 9 along with the grouped wave trains. In the same figure, a comparison between the expected (theoretical) and the measured BLW is also shown (to a larger scale) for these two cases.

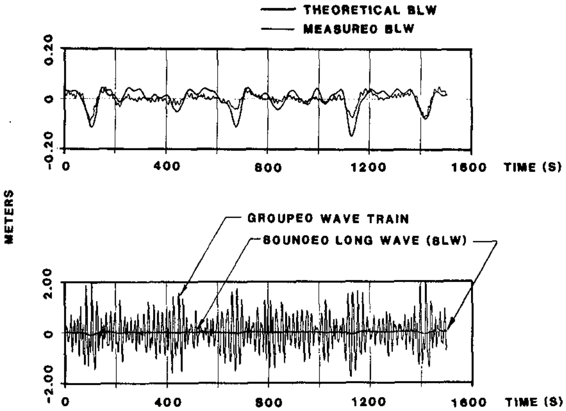
The measured BLW was extracted from the total grouped wave train by applying a low pass filter whereas the expected BLW was computed by theoretical relationships, from the measured wave train using a cut-off frequency which excludes the measured long wave.

In the first case, where proper compensation accounted for the spurious long waves, the agreement between the measured and expected values of BLW is satisfactory: the set-down under each group is well reproduced and the small discrepancies found in amplitude are only in the order of millimetres in the model. On the other hand, where no compensation is done, the amplitudes and especially phases of the BLW are different from the theoretical predictions. The change in phases results in an improper set-down (or cross-over from a set-up to a set-down) under the wave groups. This is mainly due to the standing wave pattern caused by the free long waves.

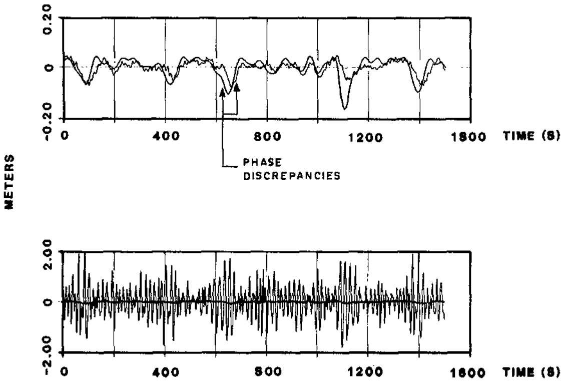
The correct reproduction of the BLW can also be checked by its propagation characteristics. Figure 10 shows an example of the propagation of the Bounded Long Wave in a flume, for three distances from the waveboard. With compensation, the set-down under the groups is well maintained during propagation, while with no compensation important amplitude and phase changes can be detected. This means that, in tests where no suppression of the spurious components is made, the response of the vessel could be quite different (high or low) depending upon the position of the test structure in the flume.

The vessel response, in terms of mooring line forces and vessel movements, for the two wave trains presented in Figure 9, is summarized in Table 1.

The two wave train records had similar time and frequency domain characteristics. The peak frequency of the SIWEH spectrum and the groupiness factor were the same as well as the peak period and the characteristic wave height. The results show, that both the RMS and maximum values of the mooring line forces (in tonnes) and vessel motions (meters, radians) were generally higher when the spurious long waves were properly suppressed (WC). This is possibly due to the proper timing of the set-down, causing an increase in velocity due to the slightly shallower water conditions, resulting in a larger response of the vessel with the higher waves of the groups. With no compensation (NC) for spurious long waves, the set-down is less, resulting in less vessel response. Table 1 for motions shows that with compensation the main component excited is sway for this particular wave input and incidence angle.

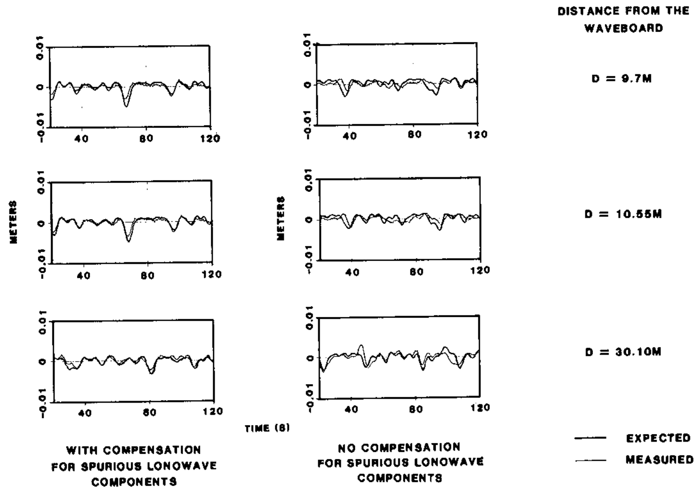


WITH COMPENSATION FOR
SPURIOUS LONG WAVE COMPONENTS



NO COMPENSATION FOR
SPURIOUS LONG WAVE COMPONENTS

FIG.9 BOUNDED LONG WAVE COMPONENTS IN THE FLUME (WITH SHIP)



WITH COMPENSATION FOR SPURIOUS LONGWAVE COMPONENTS

NO COMPENSATION FOR SPURIOUS LONGWAVE COMPONENTS

FIG.10 BOUNDED LONGWAVE COMPONENTS ALONG THE FLUME
(NO SHIP)
(MODEL UNITS)

When considering the response of a moored structure, the heave exciting force may be assumed to be:

$$F_e = \beta_1 \eta(t) + \beta_2 \eta^2(t)$$

where β_1 and β_2 are coefficients and η is the water surface elevation [NAESS (1978)]. This means that the heave motion of the vessel is related to the square of the water surface elevation $\eta^2(t)$, or in this case to the SIWEH function. This relationship is well illustrated in Figure 11 where the second order heave motion was extracted from the measured response by low pass filtering. Figure 11 also presents a comparison of the heave response between the two cases of wave generation discussed. In the first case, the long wave component of the heave response is well correlated to the SIWEH (i.e. amplification under the groups, whereas a cross-over phase shift occurs for the non-compensated free long waves. The RMS heave motions are much the same in either case.

CHAR. WAVE HEIGHT HCHR (M)	GROUPIHESS FACTOR G.F	STERH (T)	STERH BREAST (T)	STERN SPRING (T)	BOW SPRIHG (T)	BOW BREAST (T)	BOW (T)	STERN FEHDER (T)	BOW FEHDER (T)	
2.53	0.81	57.2 8.1	86.3 12.1	54.9 6.0	198.1 17.4	147.7 20.4	61.1 7.4	657.2 107.1	1210.5 197.0	N.C
2.55	0.60	71.4 7.05	112.1 14.1	71.1 9.2	215.5 22.0	146.5 23.3	85.6 8.2	982.9 130.2	1273.1 202.3	W.C

FORCES

CHAR. WAVE HEIGHT HCHR (M)	GROUPIHESS FACTOR G.F	SURGE (M)	SWAY (M)	HEAVE (M)	ROLL (RAD)	PITCH (RAD)	YAW (RAD)	
2.53	0.81	2.53 .64	3.85 .72	.78 .21	.022 .006	.019 .005	.025 .010	N.C
2.55	0.80	2.50 .88	5.10 .87	.76 .21	.018 .006	.018 .005	.029 .011	W.C

MOTIONS

MAX
RMS

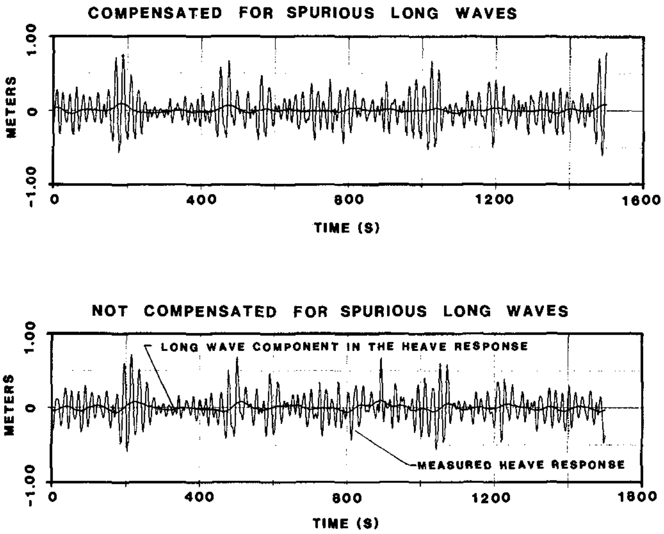
N.C - NO COMPENSATION FOR SPURIOUS LONG WAVES
W.C - WITH COMPENSATION FOR SPURIOUS LONG WAVES

TABLE 1

EFFECT OF LONG WAVE COMPENSATION ON VESSEL RESPONSE

$$f_{p\,(\text{SIWEH})} = 0.004\text{Hz}$$

$$f_p = 0.05\text{Hz}$$


COMPENSATED FOR SPURIOUS LONG WAVES

NOT COMPENSATED FOR SPURIOUS LONG WAVES

FIG.11 MEASURED HEAVE MOTION

Since the above results indicate that the response of the vessel is a function of the long wave components, it appears that proper compensation for spurious long wave components is required, in model studies, in order to determine realistic mooring line forces and vessel movements.

The results presented in the next section, on the relationship of the SIWEH to the slow drift oscillations of the vessel, were therefore investigated using proper suppression for the free long waves.

6.0 EFFECT OF WAVE GROUPING ON SLOW DRIFT OSCILLATIONS OF THE VESSEL

In order to investigate the relationship between the wave grouping present in a time series and the resulting slow drift oscillations of the vessel, three sets of wave conditions were generated in the flume using the technique previously described. These wave trains, measured in the flume, had identical variance spectral densities but different SIWEH spectra. Since the Groupiness Factor GF is directly related to the SIWEH spectrum GF = $\sqrt{m_{\varepsilon_0}}/m_0$, these three wave records, shown in Figure 12, had different groupiness factors ranging from 0.46 to 1.03.

The maximum and the RMS values of the vessel movements and the resulting mooring loads, measured under the three wave conditions, are summarized in Table 2. These results indicate that the response of the vessel increases with increasing groupiness factor in spite of the fact that the characteristic wave height and the peak period of the sea state were similar. The horizontal oscillations, surge, sway and yaw, which are sensitive to excitation by long wave components, increase when the amplitude of the long waves generated by the groups increases, resulting in increased mooring line forces.

The results of these investigations are illustrated in Figures 13 and 14 in the form of spectral plots. Figure 13 presents the spectra of mooring line forces for three typical mooring lines while the spectra of horizontal motions are shown in Figure 14.

The results indicate that a distinct correlation exists between the wave grouping and the vessel response. Therefore, in model studies, a sea state cannot be represented solely by its variance spectral density, peak period and significant wave height without considering its time domain characteristics. In other words, the wave grouping is an important parameter to be taken into account in the assessment of vessel response.

It should be mentioned that the experimental results were somewhat limited due to the narrowness of the flume to small angles of heading (30°) of the vessel relative to the waves. Further work in a wider basin may well yield more dramatic response comparisons for other heading angles, under-keel clearances, and vessel loading conditions.

In a recent study, Spangenberg (1980), was able to show a similar correlation between the wave grouping and the slow drift oscillation of a semi-submersible. The synthesis technique used in that work does not, however, allow an easy control of wave grouping characteristics (well defined periods and groupiness factors). Furthermore, no compensation was done for the spurious long wave components.

The concept of SIWEH can also be used in numerical models as input excitation functions for the slow drift oscillations.

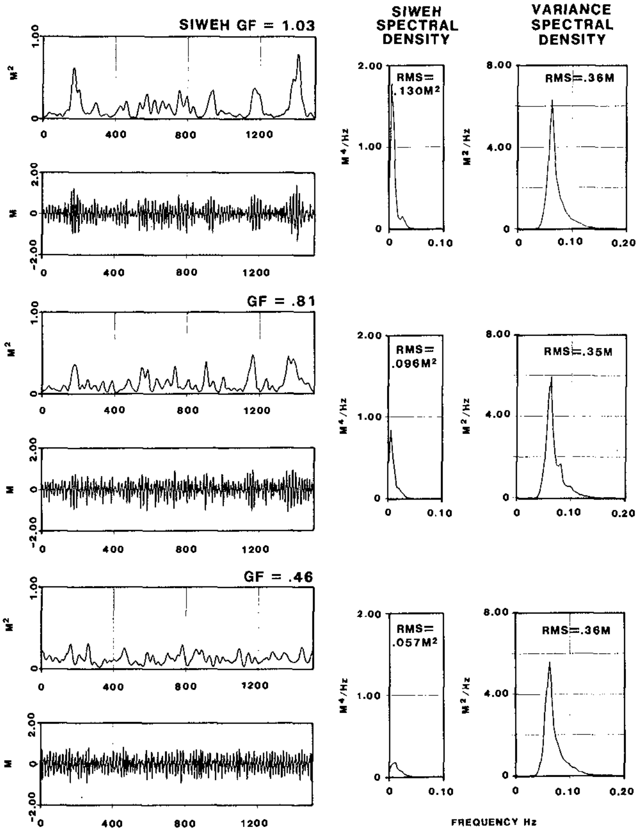


FIG. 12 WAVE TRAINS WITH COMMON VARIANCE SPECTRAL DENSITIES BUT DIFFERENT GROUPINESS FACTORS

CHAR. WAVE HEIGHT HCHR (M)	GROUPINESS FACTOR G.F	STERN (T)	STERN BREAST (T)	STERN SPRING (T)	BOW SPRING (T)	BOW BREAST (T)	BOW (T)	STERN FENDER (T)	BOW FENDER (T)
1.44	1.03	49 2.99	99 7.49	93 9.58	39 4.59	71 9.45	52 3.74	990 120.24	949 128.99
1.40	0.91	44 2.74	57 9.99	37 4.44	39 4.37	93 9.09	45 3.22	756 119.79	722 125.79
1.42	0.46	43 2.38	52 9.94	33 3.79	34 3.39	97 9.32	49 3.92	721 115.29	919 142.32

FORCES

CHAR. WAVE HEIGHT HCHR (M)	GROUPINESS FACTOR G.F	SURGE (M)	SWAY (M)	HEAVE (M)	ROLL (RAD)	PITCH (RAD)	YAW (RAD)
1.44	1.03	1.80 0.491	3.14 0.440	0.33 0.077	0.014 0.004	0.010 0.003	0.018 0.004
1.40	0.91	1.39 0.409	1.90 0.319	0.33 0.079	0.013 0.004	0.009 0.003	0.015 0.004
1.42	0.49	1.04 0.305	1.93 0.357	0.29 0.075	0.013 0.004	0.019 0.003	0.014 0.004

MAX RMS

MOTIONS

TABLE 2

EFFECT OF GROUPINESS FACTORS ON VESSEL RESPONSE

$f_{p\,(\mathrm{SIWEH})} = 0.004$ Hz

fp = 0.06 Hz

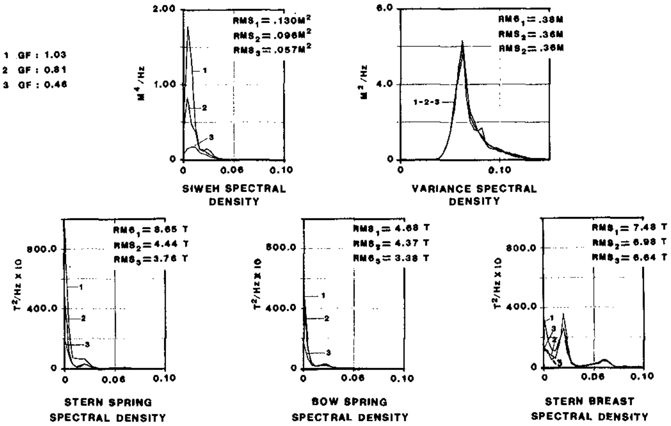


FIG.13 EFFECT OF GROUPINESS FACTORS ON MOORING LINE FORCES

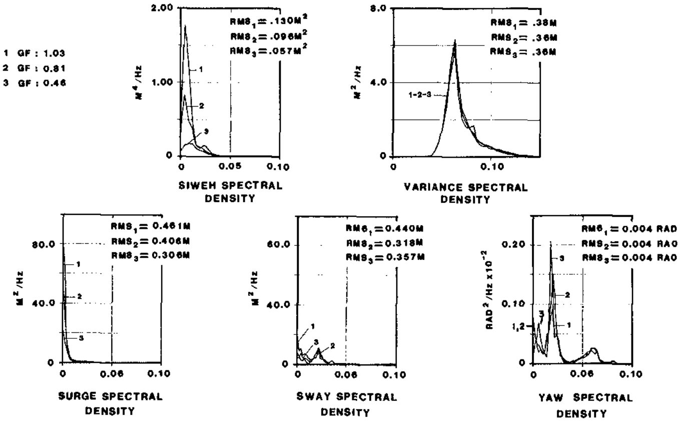


FIG.14 EFFECT OF GROUPINESS FACTORS ON VESSEL MOTIONS

7.0 CONCLUSIONS

Representing a sea state solely by its variance spectral density has been found to be insufficient for modelling the slow drift oscillations of the vessel.

The synthesis technique, used to generate realistic sea states in the model, has successfully illustrated the correlation between the slow drift oscillations and the wave grouping.

The results show that the wave grouping, present in irregular waves, is an important parameter to be taken into account in the assessment of vessel response.

It has been shown that a correct reproduction of Bounded Long Wave Components is required, in model studies, in order to have a realistic response of the vessel.

8.0 ACKNOWLEDGEMENTS

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