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VIBRATIONS: SESSION B: VIBRATION IN TRANSPORT VEHICLES

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EVALUATION OF THE MOTION AND SPEED CHARACTERISTICS OF A SHIP IN IRREGULAR SEAS

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Introduction

The ship, which is assumed rigid, has motions which are usually considered to occur in the six degrees of freedom and known as surge, sway, heave, roll, pitch and yaw. None of these motions occur singly, they are coupled depending on the wave direction. In beam seas, roll and sway are dominant whilst in head seas, pitch and heave predominate. Heave, pitch and sometimes surge are treated under the heading of 'seakeeping' and the study of sway and yaw motions have formed the subject of 'manoeuvring', whilst roll motion is treated with both. Briefly, a ship has good seakeeping qualities if it is capable of performing its design task in the roughest sea with the minimum of interruption.

By utilising random process theory, St Denis and Pierson (1) developed a theoretical model for the random ship wave motion system. The derived statistical information of the ship motion enables the prediction of suitable safety limits for the ship's operability. In this paper, the determination of the ship response and the necessary seakeeping criteria for a ship in irregular waves are described.

Wave Analysis

Wave data is collected from visual observations on merchant ships during their travel over the oceans as well as from weather ships stationed at fixed positions. A vast amount of data has been compiled and tabulated by Hogben and Lumb (2) covering fifty sea areas on the main trade routes.

For theoretical analysis the sea condition is described by a wave spectrum. The one most used for a fully developed long crested seaway is that derived by Pierson and Moskowitz (3). This is based on the actual spectral analysis of 400 wave records taken on weather ships in the North Atlantic and given by,

$$\Phi(\omega) = A\,\omega^{-5} e^{-\frac{B}{\omega^4}} \qquad 0 < \omega < \infty$$

where A and B are constants defined as follows,

1. Only significant wave height, $h_{1/3}$ known, then $A = 8.1g^2 10^{-3}$ and $B = 3.11\, h_{1/3}^{-2}$ where $h_{1/3}$ is in metres and $g(m.s^{-2})$ is the gravitational constant.

2. Significant wave height and characteristic period, T_1 known, then $A = 173\ h_{1/3}^2\ T_1^{-4}$ and $B = 691\ T_1^{-4}$, where $T_1 = 2\pi\ m_o\ m_1^{-1}$ may be taken approximately as the observed wave period and the spectral moments

$$m_n = \int_0^\infty \omega^n\ \Phi\ (\omega)\ d\ \omega \qquad\qquad n = 0,1,2,\ \ldots$$

These forms of the wave spectrum are currently the best theoretical models available but their correlation with actual wave spectra are not always in good agreement. They apply to 'fully developed seas' which only exist in the ocean for short periods since the varying ocean surface is highly dependent on the prevailing meteorological conditions.

Although both spectral forms express the same wave energy content they differ in various ways. The frequencies at which the spectral peaks occur are

$\omega = 1.26\ h_{1/3}^{-\frac{1}{2}}$ in (1) and $\omega = 4.85\ T_1^{-1}$ in (2), and agreement is obtained only when $T_1 = 3.85\ h_{1/3}$.

Although the vast majority of the wave information is visual, correlation between the observed wave height and measured significant wave height is good. Unfortunately, the observed and measured wave periods have poor correlation. In practice, if the information is available the spectral form (2) is used in preference to (1).

Modifications to these spectral forms are employed when the seaway is short-crested by defining a wave spectrum which accounts for the spread of waves $\pi/_2$ on either side of the predominant wave direction.

The standard International Towing Tank Conference (ITTC) form is,

$$\Phi(\omega,\ \mu) = 2\pi^{-1}\ \Phi(\omega)\ \cos^2\mu \qquad\qquad \mu \leq {}^{\pi}/2$$

where μ is the angle of spread.

Ship Response

In order to determine the motion response of a ship travelling in an irregular seaway, with speed V, it is assumed that,

a. The ship-wave system is linear so that the motion response of the ship to any regular sinusoidal wave is a linear function of the wave's amplitude and is also sinusoidal with a frequency equal to the frequency of encounter.

b. The principle of superposition is valid with the result that the motion response of the ship to the seaway is the sum of the responses to the individual wave components composing the seaway.

It has been shown (1) that the analysis of linear systems with random ergodic inputs and outputs can be applied to the ship-wave system. In particular the wave input has spectral density $\Phi(\omega)$ and the ship's motion output is given by,

$$\Phi_m(\omega) = |H(\omega)|^2\ \Phi(\omega)$$

where $|H(\omega)|^2$ is the square magnitude of the receptance of the motion under consideration. In practice, the non-dimensional form of

$|H(\omega)|^2$ is referred to as the response amplitude operator (RAO) and may be calculated either theoretically using ship theory (4) or determined from oscillatory tests. Knowing $|H(\omega)|^2$ and $\Phi(\omega)$, the motion spectrum may be determined and the statistical moments m_n ($n = 0,1,2 \ldots$) calculated, as illustrated in Figure 1.

In practice the frequency domain employed is not absolute wave frequency, ω, but the encounter frequency, ω_e, given by

$$\omega_e = \omega - V\omega^2 g^{-1} \cos \chi$$

where χ is the angle between ship and waves. It is a constant in a long crested sea but variable for a short-crested sea. For ships in head seas, $0.5\pi < \chi < 1.5\pi$, $\cos \chi$ is always negative and the frequency of encounter is always positive. However, for ships in following seas, $0 < \chi \leq \pm 0.5\pi$, $\cos \chi$ is always positive and the frequency of encounter may be positive or negative depending on whether the waves travel faster than the ship or the ship overtakes the waves respectively. In this latter case the ship appears to be in a head sea condition and the frequency of encounter has to be re-defined as

$$\omega_e = | \omega - V\omega^2 g^{-1} \cos \chi |$$

The transformation of the spectra from the frequency domain ω to ω_e is given in general by, $\Phi(\omega_e)d\omega_e = \Phi(\omega)d\omega$, but in following seas such transformations are troublesome due to the relationship between the frequency domains. These are discussed in (1,5).

Criteria

Random process theory has been applied to several seakeeping problems, including the prediction of maintainable ship speeds in head seas. Ships' captains are obliged to alter speed when navigating in head seas to avoid various undesirable facets of ship behaviour including green water on the deck, excessive vertical accelerations and slamming. The speed change thought necessary depends, for a particular ship, on the captain's concept of the acceptable values of the frequency of occurrence and the severity of each facet.

Deck wetness due to green water occurs when the ship relative motion exceeds the local freeboard restricting activity and visibility and, when severe, can cause considerable damage. Its probability of occurrence,

$$P(\text{wet}) = e^{-F^2/2m_{or}}$$

where F is the local freeboard and m_{or} is the zero moment of the relative motion spectrum which is a function of the position on the ship, speed of the ship and sea state.

The probability of occurrence of a particular magnitude of vertical acceleration which could, for example, affect passenger comfort or impair crew efficiency is given by,

$$P(\text{accl}) = e^{-\frac{C^2}{2m_{4a}}}$$

where C is an acceptable acceleration limit at a particular station and m_{4a} is the fourth moment of the absolute motion spectrum.

Slamming is deemed to occur when both the relative motion exceeds the draft, T, and the impact velocity on re-entry exceeds a threshold value V_*. Its probability of occurrence is

$$P(\text{slam}) = e^{-\left[\frac{T}{2m_{or}} + \frac{V_*^2}{2m_{2r}}\right]}$$

It is undesirable because it can cause extensive local damage to the hull and excessive vibrations throughout the ship.

If acceptable limits of the probabilities P(wet), P(accl) and P(slam) and the severities C and V_* were known together with the moments then an operational envelope similar to Figure 2 could be calculated. Currently alternative ship designs may be compared using this method with arbitrary values of the limits at an early design stage to quantify the effect of some change in hull shape on the maintainable ship speed.

The above application is useful to the designer making decisions between alternative solutions. However, the ship's operational speed is usually the decision of the captain and will depend on his experience and the actual sea state. For this reason, there is subjective scatter on the predicted speed envelope. One attempt to increase the information available to captains is the introduction on some container ships of bow emergence indicators. Captains can adjust their ships' speed with reference to the frequency of bow emergency thus reducing the probability of severe slamming, whilst not making too large a decrease of speed. However the economic balance between fast crossings and large repair bills can easily be upset by one really bad slam.

Several papers have suggested wetness limits (6) and a concensus suggests that green water could be shipped 5 times in 100 oscillations (P(wet) = .05). The effect on the predicted speed of varying P(wet) is shown in Figure 3. Changes of the slamming and acceleration probabilities have similar effects on their respective envelopes.

References

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2. W Hogben and F E Lumb 1967. HMSO
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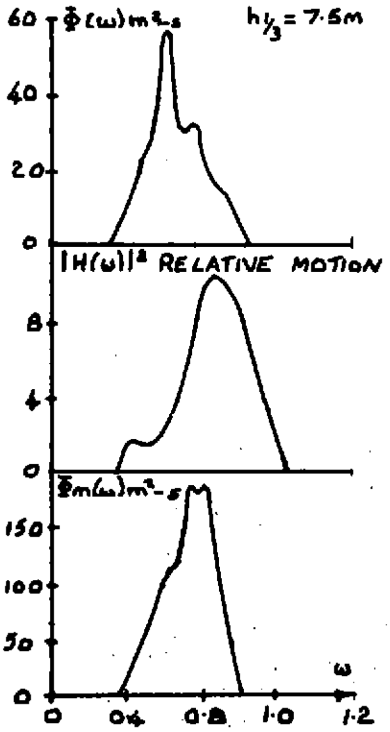

FIG. 1

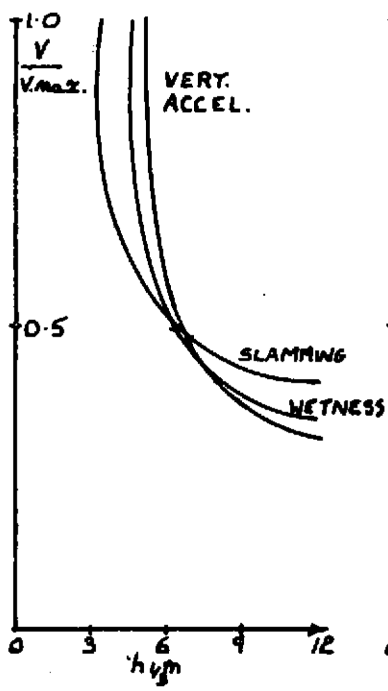

FIG. 2

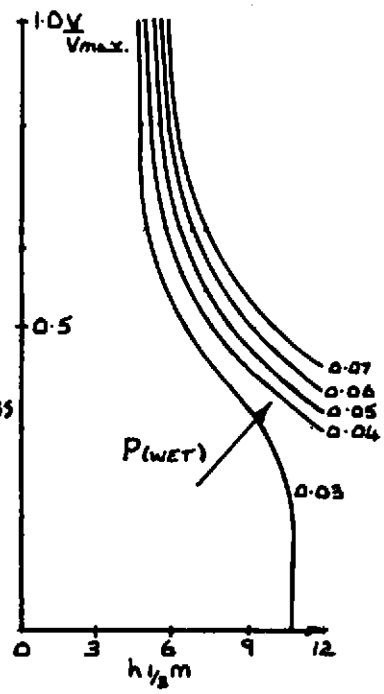

FIG. 3