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Updated by	Approved
Load and Responses Committee of 23rd ITTC	23rd ITTC
Date	Date 2002

Predicting Power Increase In Irregular Waves From Model Experiments In Regular Waves

1 PURPOSE OF PROCEDURE

Methods of predicting power increase in irregular waves from response curves measured on ship models in regular waves are described. The analysis of results of experiments carried out at model self-propulsion point to give predictions of performance at ship propulsion point is considered in detail. A calculation method suitable for adoption as a standard for routine ship prediction is proposed.

2 ON PREDICTING POWER INCREASE IN IRREGULAR WAVES FROM MODEL EXPERIMENTS IN REGULAR WAVES

2.1 Introduction

The problem of predicting the power increase required to maintain speed in a specific sea state from model experiments in regular waves might be considered in two parts. First is the prediction from response curves, of the power increase of the model in irregular waves. Second is the prediction of the power increase of the ship from the results of model experiments.

The first part of the problem may in principle be avoided by running the model in irregular waves. However this is not in general a satisfactory solution because the results, which are less precise than those obtained in regular waves, apply only to the particular ship length and spectra for which the experiments were carried out. The calculation methods described below all enable predictions of performance in irregular waves to be made for any desired ship length and sea spectrum.

Model experiments in waves are usually carried out at model self-propulsion point. The experiments at ‘model self-propulsion point’ are those conducted without the consideration on the difference of the skin-friction coefficient between a model ship and the corresponding real ship. If the skin-friction difference is corrected by, e.g., towing the model ship with the force that compensate for the skin-friction difference, then the performance at ‘ship propulsion point’ is obtained.

A closer approximation to the performance of full size ships should be obtained by running the model with a range of tow forces covering the range of skin friction and overload corrections as in still water experiments. This is not practical for routine experiments because of the time and expense involved. On the other hand, any curtailment of such a programme would again result in data which apply only to a particular ship length and skin friction estimate, and be incapable of generalisation.

A comprehensive series of experiments in waves with three typical single screw models in which the propeller loading was varied over a wide range was described by Moor and Murdey (reference 1). Their results showed that the power increases at loadings less than model self-propulsion point were less than the power increase at model propulsion point, but propeller thrust, torque and rate of rotation increases became greater as the loading was reduced, the magnitude of the difference depending on both ship length and sea state.

This paper reviews three methods in common use for predicting the power increase of ships in a given sea state from data measured on models run at model self-propulsion point, and presents evidence upon which the choice of a method for use as a standard may be based.

2.2 Summary of Calculation Methods

On the assumption that the mean increases in delivered power, and propeller torque and rate of rotation could be taken to be proportional to the square of the wave height, Gerritsma, van den Bosch and Beukelman (reference 2) showed that the mean increases required to maintain the speed of a model in irregular waves could be calculated from response curves measured in regular waves by the following formulae:

Mean increase in power,

$$_m\delta P = \frac{2}{\zeta_a{}^2}\int_0^\infty \delta P(\omega) S(\omega)\, d\omega \tag{1}$$

mean increase in propeller torque,

$$\delta Q = \frac{2}{\zeta_a{}^2}\int_0^\infty \delta Q(\omega) S(\omega)\, d\omega \tag{2}$$

and mean increase in propeller rate of rotation

$$\delta n = \frac{2}{\zeta_a{}^2}\int_0^\infty \delta n(\omega) S(\omega)\, d\omega \tag{3}$$

in which $\delta P(\omega)$, $\delta Q(\omega)$ and $\delta n(\omega)$ are the increases in delivered power, and propeller torque and rate of rotation at model self-propulsion point measured in regular waves with frequency ω s^{-1} and amplitude ζ_a m, and $S(\omega)$ $m^2 s$ is an ordinate in the spectrum of the irregular waves.

The first method of predicting the power increase of the ship uses equation (1) directly. In practice $\delta P(\omega)$ is calculated from the propeller torque and rate of rotation measured in waves and in still water using the relationship:

$$\delta P(\omega) = 2\pi\left\{\left({}_mQ_{SW} + \delta Q(\omega)\right)\left({}_mn_{SW} + \delta n(\omega)\right) - {}_mQ_{SW}\,{}_mn_{SW}\right\} \tag{4}$$

where ${}_mQ_{SW}$ and ${}_mn_{SW}$ are values of propeller torque and rate of rotation at model self-propulsion point in still water, measured in association with the experiments in waves. The results of these calculations are applied to the ship on the assumption that propeller loading has no effect on power increase and that ${}_m\delta_{P1}$ may be scaled simply by a factor $(\text{scale})^{3.5}$. This method of calculation is referred to below as the direct power method.

In the second calculation method, equations (2) and (3) are used to calculate the mean increases in propeller torque and rate of rotation at model self-propulsion point which are then combined with still water values at ship propulsion point to give a power increase.

This method of predicting the power increase is referred to below as the torque and rate of rotation method.

The third calculation method to be considered in this paper was described by Vossers, Swaan, and Rijken (reference 3) and makes use of the thrust increase measured in regular waves at model self-propulsion point. This prediction method is referred to below as the thrust method.

2.3 Data

Full details of the ship forms, experimental techniques and calculations are given in references 1 and 4

2.4 Choice of a Method for Use as a Standard

The choice between the direct power and the torque and rate of rotation methods of prediction may be made on both theoretical and practical grounds. Equations (1) and equations (2) and (3) upon which the direct power and torque and rate of rotation methods respectively are based, are derived in reference 2 from a similar equation for the calculation of resistance increase, on the assumption that power and propeller torque and rate of rotation are proportional to resistance. This assumption is shown in reference 2 to be more nearly true for power and torque than for rate of rotation, and equation (3) may therefore be expected to be less accurate than either of equations (1) and (2). Thus the direct power method, based on equation (1), is to be preferred.

A practical advantage of the power method is that it gives a result that is independent of the results of overloaded self-propulsion experiments in still water. The torque and rate of rotation method does require the results of overload experiments in still water and the result of the calculation, therefore, depends on the method of analysis of those experiments and the choice of loading.

Another advantage of the use of the direct power method in practice is that estimates of the power increase based on equations given in reference 1 do not depend on particulars of the propeller, which is not true of estimates of increases in propeller torque and rate of rotation. Thus the power increase for a range of forms of different length can be estimated without consideration of propeller dimensions or changes in hull performance in calm water, both of which must be taken into account if the torque and rate of rotation method is used.

A disadvantage of the direct power method becomes apparent when the results of predictions are combined to give simultaneous values of power, and propeller torque and rate of rotation. In these cases independent calculations of the power increases and increases in propeller torque and rate of rotation would lead to inconsistent values of total power, torque and rate of rotation and it is necessary to derive the total torque or rate of rotation from the total power and either rate of rotation or torque respectively.

It is not possible to predict the power increase of a ship from data measured on a model at model self-propulsion point without making some assumption about the effect of the overload correction on performance in waves.

A calculation method using thrust data in conjunction with the open water characteristics of the propeller in calm water involves unjustified assumptions concerning the effect of waves on the action of the propeller behind the hull, and leads to misleading results and erroneous comparisons between ship forms.

Of the two other methods considered, one, using power response curves at model self-propulsion point, leads to an overestimate compared with values obtained from models run with the overload correction, and the other, using response curves of propeller torque and rate of rotation at model self-propulsion point in conjunction with still water values at ship propulsion point leads to an underestimate.

On consideration of all these aspects it is concluded that the direct power method is suitable for use as a standard for the routine prediction of ship performance in head seas.

2.5 Conclusions

The direct power method has advantages both in theory and in practical use, and it was therefore proposed at the 13th ITTC meeting as a suitable interim standard method for routine ship predictions. In the 14th ITTC meeting, however, it was agreed that, since the direct power method was not necessarily employed by many organizations, all the possible alternative methods should be examined before we finally establish an ITTC standard. One of such alternatives may be the thrust identity method. In this method, the mean increase of resistance is calculated from the response curve measured in regular waves assuming that the resistance increase is proportional to the square of wave height. The power increase in a specific sea state is calculated in exactly the same way as the calculation of the necessary power in still water. Wind force can be accounted for by simply adding the force to the resistance increase. The details of this method are described in reference 7.

Further work is required to derive more detailed correction factors by which the results of experiments at model self-propulsion point may be multiplied to give estimates of performance at ship propulsion point. Experiments at ship propulsion point which may lead to such correction factors should be carried out in addition to, and not instead of, experiments at model self-propulsion point so as not to prevent the building up of data required to establish standards of performance in waves.

3 PARAMETERS

3.1 Parameters To Be Taken Into Account

D Propeller diameter, m.

k_P Power coefficient for propeller in open water = $nQ/\rho\ D^2 v^3$

k_U Thrust coefficient for propeller in open water $= T/\rho . D^2 v^2$

L_{PP} Length between perpendiculars, m.

n Propeller rate of rotation in calm open water per second.

$_m n_{SW}$ Propeller rate of rotation in still water at model self-propulsion point, revolutions per second

$_s n_{SW}$ Propeller rate of rotation in still water at ship self-propulsion point, revolutions per second

δn Increase in propeller rate of rotation in irregular waves, at model self-propulsion point, revolutions per second.

$\delta n(\omega)$ Increase in propeller rate of rotation in regular waves, at model self-propulsion point, revolutions per second.

$_m\delta_{P1}$ Increase in delivered power in irregular waves at model self-propulsion point, calculated from response curve of power at model self-propulsion point.

$_s\delta_{P1}$ Increase in delivered power in irregular waves at ship propulsion point calculated from response curve of power at ship propulsion point.

$_m\delta_{P2}$ Increase in delivered power in irregular waves, at model self-propulsion point calculated from response curves of propeller torque and rate of rotation at model self-propulsion point in conjunction with still water data at model self-propulsion point

$_s\delta_{P2}$ Increase in delivered power in irregular waves at ship propulsion point calculated from response curves of propeller torque and rate of rotation at model self-propulsion point in conjunction with still water data at ship propulsion point

$_s\delta_{P3}$ Increase in delivered power in irregular waves at ship propulsion point calculated from response curves of propeller torque and rate of rotation at ship propulsion point in conjunction with still water data at ship propulsion point

$_s\delta_{P4}$ Increase in delivered power in irregular waves at ship propulsion point calculated from response curve of thrust at model self-propulsion point in conjunction with open water characteristics of the propeller in calm water and still water data at ship propulsion point.

$\delta P(\omega)$ Increase in delivered power in regular waves at model self-propulsion point

Q Propeller torque in calm open water, Nm.

$_m Q_{SW}$ Propeller torque in still water at model self-propulsion point, Nm.

$_s Q_{SW}$ Propeller torque in still water at ship propulsion point, Nm.

δQ Increase in propeller torque in irregular waves at model self-propulsion point, Nm.

$\delta Q(\omega)$ Increase in propeller torque in regular waves, at model self-propulsion point, Nm.

$S(\omega)$ Spectrum energy density ordinate, m^2 /radian/s.

T Propeller thrust in calm open water, N.

δT Increase in propeller thrust in irregular waves at mode self-propulsion point, N.

δ **$T(\omega)$** Increase in propeller thrust in regular waves at model self-propulsion point, N.

v Propeller speed of advance in open water, m/s.

ζ_a Wave amplitude of regular waves, m.

ρ Density of water, kg/m^3

ω Wave frequency, radians/s.

4. VALIDATION

4.1. Uncertainty Analysis

None

4.2. References

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On Proposed Interim Standard Procedure Predicting Power Increase in Head Waves in Commercial Practice. Materials of Interest, International Towing Tank Conference, Berlin/Hamburg 1972.

4.3. Benchmark Tests

1) Seagoing Quality of Ships
(7th 1955 pp.247-293)
A Model of the Todd-Forest Series 60, Cb=0.60:
7 tanks used 5ft. models, 2 tanks used 10 ft. models, and 1 tank used 16 ft. model Froude Numbers 0,0.18,0.21,0.24,0.27 and 0.30
The Ratio wave height to the Length of the

Model:	1/36	1/48	1/60	1/72
for Wave Length	0.75L	1.0L	1.25L	1.5L

2) Comparative Tests in Waves at Three Experimental Establishments Using the Same Model
(11th 1966 pp.332-342)
British Towing Tank Panel: A 10 ft. Fibre-

Glass Model of the S.S. Cairndhu
A Series of Experiments on a Ship Model in Regular Waves Using Different Test Techniques
Data Obtained in Irregular and Transient Waves and Some Result Predicted by the Theory (Based on Korvin Kroukovsky's Work and Employing the Added Mass and Damping Coefficients Calculated by Grim)

3) Full Scale Destroyer Motion Measurements (11th 1966 pp.342-350)
Full Scale Destroyer Motion Tests in Head Sea
Comparison among Motion Response Obtained from Full Scale Tests, Model Experiments and Computer Calculations
The Destroyer H.M. "Groningen" of the Royal Netherlands Navy
A Scale Ration 40 to 1

4) Comparison of the Computer Calculations of Ship Motions (11th 1966 pp.350-355)
Ship Response Functions for the Series 60 C_B=0.70 Parent Form

5) Computer Program Results for Ship Behaviour in Regular Oblique Waves (11th 1966 pp.408-411)
Series 60, CB=0.60 and 0.70 Parent Form
DTMB Model 421OW and 4212W

6) Experiments in Head Seas

6-1) Comparative Tests of a Series 60 Ship Model in Regular Waves (11th 1966 pp.411-415)
Series 60 C_B=0.60

6-2) Experiments on Heaving and Pitching Motions of a Ship Model in Regular Longitudinal Waves (11th 1966 pp.415-418)
Series 60 C_B=0.60

6-3) Experiments on the Series 60, C_B=0.60 and 0.70 Ship Models in Regular Head Waves
(11th 1966 pp.418-420)
Series 60, C_B=0.60 and 0.70

6-4) Comparison of Measured Ship Motions and Thrust Increase of Series 60 Ship Models in Regular Head Waves (11th 1966 pp. 420-426)
Series 60, C_B=0.60 and 0.70

6-5) Estimation of Ship Behaviour at Sea from Limited Observation (11th 1966 pp.426-428)

7) Computer Results, Head Seas

7-1) Theoretical Calculations of Ship Motions and Vertical Wave Bending Moments in Regular Head Seas (11th 1966 pp. 428-430)
Series 60, C_B=0.70

7-2) Comparison of Computer Program Results and Experiments for Ship Behaviour in Regular Head Seas (11th 1966 pp.430-432)
Series 60, C_B=0.60 and 0.70

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7-4) Comparison of Calculated and Measured Heaving and Pitching Motions of a Series

60, CB=0.70 Ship Model in Regular Longitudinal Waves (11th 1966 pp.436-442)
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7-5) Computer Calculations of Ship Motions (11th 1966 pp.442)

7-6) Comparison of the Computer Calculations of Ship Motions and Vertical Wave Bending Moment (11th 1966 pp. 442-445)
Series 60, C_B=0.60 and 0.70

8) Comparison of the Computer Calculations for Ship Motions and Seakeeping Qualities by Strip Theory
(14th 1975 Vol.4 pp.341-350)
A Large-Sized Ore Carrier

9) Comparison on Results Obtained with Computer Programs to Predict Ship Motions in Six Degrees of Freedom
(15th 1978 pp. 79-90)
S-175,C_B = 0. 572

10) Comparison of Results Obtained with Compute Programs to Predict Ship Motions in Six-Degrees-of-Freedom and Associated Responses (16th 1981 pp.217-224)
To Identify the Differences in the Various Strip Theories and Computation Procedures utilised by the Various Computer Programs and Provide Guidance for Improvement if Necessary
S-175 Container Ship for Fn = 0.275

11) Analysis of the S-175 Comparative Study (17th 1984 pp.503-511)

12) S-175 Comparative Model Experiments (18th 1987 pp.415-427)
13) Rare Events (19th 1990 pp.434-442, Seakeeping)

14) Validation Standards of Reporting and Uncertainty Analysis Strip Theory Predictions (19th 1990 pp.460-464)

15) ITTC Database of Seakeeping Experiments (20th 1993 pp.449-451)
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16) Validation of Seakeeping Calculations (21st 1996 pp.41-43)
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S-175, High Speed Marine Vehicle