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Prediction of Speed and Behaviour of a Ship in a Seaway

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Summary

A computer program has been developed to calculate speed and behaviour of a ship in a seaway. In this stage the program is suitable for seagoing vessels in head waves. In determining the speed, two factors are considered: the natural speed reduction due to added resistance caused by wind and waves and the voluntary speed reduction by the ship's captain, in order to prevent severe motions.

1 Introduction

For almost twenty years now, a ship's captain can make use of routing advises from weather routing departments like that from the K.N.M.I. (Royal Netherlands Meteorological Institute) at De Bilt [1]. With a known rough weather pattern in the ocean an optimum ship’s route can be found with a minimum travelling time, fuel consumption or risk of damage of the ship and its cargo. These routing advises, are based on the momentary and expected wind and waves and the ship’s reaction to them. The forecast of wind and waves is a meteorological problem. Up to now the prediction of the behaviour of a ship in a seaway - especially the ship’s speed - is based on routing experience with the ship considered or similar ships.

When routing a ship for the first time a routing officer needs reliable speed loss graphs, to read the ship’s speed as a function of wave height and mean wave direction. Developments in the last decade made it possible to calculate with sufficient accuracy the speed in still water and the natural speed reduction due to added resistance caused by wind and waves. At this theoretical speed dangerous motions can arise for the safety of crew, ship or cargo. Then the master will voluntarily reduce speed in order to prevent severe motions. Several criteria for this decision can be found in literature.
At the Ship Hydromechanics Laboratory of the Delft University of Technology a method has been developed to calculate the natural speed, the voluntary speed reduction and the behaviour of the ship at

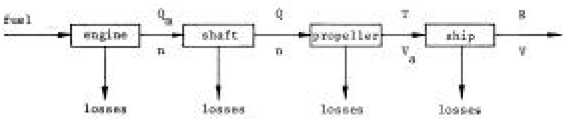
this speed in a seaway with head waves. This method has been worked out into an Algol'60 computer program, named ROUTE, which enables a practical use.

2 Calculation of Speed

Apart from wind and sea conditions, the speed of a ship in a seaway mainly depends on three aspects:

- dimensions and form of the ship's hull and superstructure,
- dimensions and characteristics of the propeller and
- output and characteristics of the propulsive machinery.

The energy flow of a ship in operation is given in the following scheme.



The propeller behind a ship is considered as an energy transformer: torque with rpm will be transformed into thrust with a mean speed of advance. At a certain steam or fuel inlet ratio of the engine there will be equilibrium between the number of revolutions and the ship's speed. This equilibrium is in such a way that two conditions are fulfilled: the torque needed by the propeller must be in equilibrium with the torque delivered by the engine and the thrust delivered by the propeller must be in equilibrium with the total resistance of the ship.
These two conditions of equilibrium are shown in two coupled equations as mentioned below:

$$Q_m(Q_0, n_0, c, n) = \frac{Q(V_a, n)}{h_m}$$

$$R_T(V, V_W, a_W, \overline{H}_{1/3}, \overline{T}, m) = T(V_a, n) \cdot \{1 - t(V, n)\}$$

where the relation between V_a and V is given by:

$$V_a = V \cdot \{1 - w(V)\}$$

At a certain engine setting these two equations are solved in the program ROUTE for every wind and sea condition as shown in Figure 1.

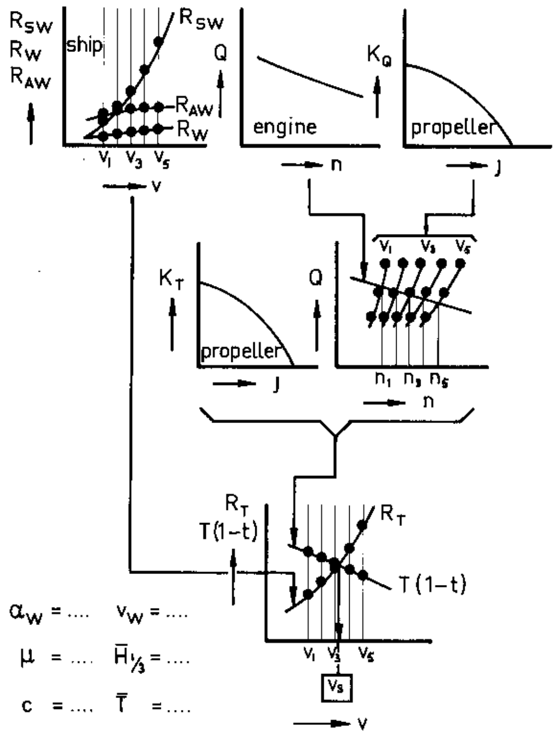


Figure 1 Scheme of Speed Calculation

For a number of ship speeds the relations between torque needed by propeller and rpm are calculated from the torque characteristics of the propeller behind the ship and an adapted wake fraction. The relation between torque delivered by the engine to the propeller and rpm is known from engine characteristics and shaft losses. These relations give a relation of equilibrium for speed and rpm, which together with the thrust characteristics of the propeller behind the ship and a thrust deduction fraction results in a resistance, which can be achieved by propeller and engine, as a function of the ship's speed. If the total resistance of the ship for a number of speeds is known by calculation the actual speed of the ship can be found.

Some parts needed for the determination of the speed are discussed in the following parts of this chapter.

2.1 Resistance

The total resistance of a ship in a seaway is divided into three parts:

- still water resistance: $R_{SW}(V)$
- wind resistance: $R_W(V, V_W, \alpha_W)$
- added resistance due to waves: $R_{AW}(V, \overline{H}_{1/3}, \overline{T}, m)$

So the relation between resistance and thrust can be written as:

$$R_{SW}(V) + R_W(V, V_W, \alpha_W) + \\ + R_{AW}(V, \overline{H}_{1/3}, \overline{T}, m) = \\ = T(V_a, n) \cdot \{1 - t(V, n)\}$$

The determination of these three components of the resistance is given in more detail in the following paragraphs.

2.1.1 Still Water Resistance

In literature several methods have been described to determine the still water resistance of a ship. These methods have been based on the results of a large number of model experiments and full-scale experiments which have been systematically or statistically transformed into graphs, tables or empirical formulas.
Up to now in the computer program ROUTE, one of the next two methods can be used:

- The method of the Shipbuilding Research Association of Japan [2]. This method has been developed for fast slender ships with a block-coefficient between 0.55 and 0.65. It is a great advantage of this method that it can be used for different loading conditions of the ship.
- The method of Lap [3] with an extension of Auf 'm Keller [4]. This method can be used for most normal and full ships in full load condition. With less accuracy a ship in light load condition can be considered as a ship in full load condition with a large breadth - draught ratio.

Both methods are valid for single-screw ships with a limited speed range. For too low a speed the resistance is extrapolated with a second-degree polynomial and for too high a speed with a third degree polynomial. No allowances are made for fouling or a bulbous bow. In the program however, it is possible to multiply the still water resistance with a correction factor.

2.1.2 Wind Resistance

For containerships and ships in ballast condition the wind resistance often is a part of the total resistance which may not be neglected. Isherwood [5] has analysed the results of wind resistance experiments carried out at different laboratories with models covering a wide range of merchant ships. He gives empirical formulas for determining the two horizontal components of the wind force and the wind-induced yawing moment on any merchant ship form for a wind from any direction. The formula and the corresponding coefficients for the wind resistance are used in the program.

2.1.3 Added Resistance due to Waves

To calculate the added resistance of a ship in a seaway a computer program, named TRIAL, is available at the Delft Ship Hydromechanics Laboratory. An earlier version of the program has been described in [6].
The ship is considered to travel in unidirectional head waves and only pitch and heave motions are determined. Added mass and damping for the ships cross-sections are calculated by using a Lewis

conformal transformation. The resulting fit to the actual cross sectional form is satisfactory for the present purpose [7].
The increase of resistance in regular waves is calculated with the method of Gerritsma and Beukelman by determining the radiated energy of the damping waves as described in [8].
The calculation in an irregular sea is based on the superposition principle for the components of the wave, motion and resistance spectra as well as on the assumption of linearity for the ship's response. In regular waves the added resistance varies as the square of the wave amplitude. In a wave spectrum the mean added resistance would then be calculated from:

$$\overline{R}_{AW} = 2\int_0^\infty \frac{R_{AW}}{z_a^2}(w_e)\cdot S_z(w_e)\cdot dw_e$$

The program TRIAL has been adapted to this special problem in the program ROUTE. For the description of the sea surface two parameter Pierson-Moskowitz wave spectra are used. For each wave spectrum, the mean added resistance is calculated as a function of the ship's speed.

2.2 Propeller Characteristics

Thrust and torque of an open-water propeller are defined by:

$$T = K_T \cdot rD^4 n^2$$

$$Q = K_Q \cdot rD^5 n^2$$

The coefficients K_T and K_Q are depending on the number of propeller blades, blade area ratio, pitch ratio and advance coefficient which is defined by:

$$J = \frac{V_a}{nD}$$

Propeller characteristics can be obtained from open-water test results of the Wageningen B-series propellers, which are frequently used in practice. At present about 120 propeller models of the B-series have been tested at the Netherlands Ship Model Basin.
The thrust and torque coefficients are expressed by Oosterveld and Van Oossanen [9] as polynomials in the number of propeller blades, blade area ratio, pitch ratio and advance coefficient. With the aid of a multiple regression analysis the significant terms of the polynomials and the values of the corresponding coefficients are determined. The polynomials are valid for open-water propeller models with Reynolds number $Rn = 2 \cdot 10^6$.
Oosterveld and Van Oossanen [10] also give polynomials to correct thrust and torque coefficients for the actual Reynolds number of the full-size B-series open-water propeller. These polynomials are used in the program.
For the propeller behind a ship the calculated torque must be corrected for this behind condition:

$$h_R = \frac{Q_{\text{open water}}}{Q_{\text{behind ship}}}$$

For single-screw ships 1.04 is a good mean value for this relative rotative efficiency, while for twin-screw ships 0.97 is advised.

2.3 Wake and Thrust Deduction

In the program, the wake fraction and the thrust deduction fraction can be estimated by very simple formulas. If one of these values is known, for instance from model tests, it is also possible to make use of this value.

Wake fraction:

- Taylor [11]
  single-screw ship:
  $w = -0.05 + 0.50 \cdot C_b$
  twin-screw ship:
  $w = -0.20 + 0.55 \cdot C_b$
- Harvald [12]

single-screw ship:

$w = w(C_b, L/B, D/L, \text{hull form})$

twin-screw ship:

$w = w(C_b, L/B)$

- A given value of the wake fraction.

Thrust deduction fraction:

- Weingart:
  single-screw ship:
  $$t = w \cdot \left(1.57 - 2.30 \cdot \frac{C_b}{C_{wp}} + 1.50 \cdot C_b \right)$$
  twin-screw ship:
  $$t = w \cdot \left(1.67 - 2.30 \cdot \frac{C_b}{C_{wp}} + 1.50 \cdot C_b \right)$$
- A given value of thrust deduction fraction - wake fraction ratio.
- A given value of the thrust deduction fraction.

The above mentioned values are valid in still water. Model tests in still water showed that wake fraction and thrust deduction fraction are practically independent of speed. It can be shown from overload tests in still water that at an increasing propeller loading and a constant number of revolutions, the wake fraction keeps constant and the thrust deduction fraction is approximately linearly decreasing with the model speed.
Experiments at the Delft University of Technology with a model of a fast cargo ship showed no difference between still water and regular waves for both fractions at the same average loading of the propeller [28].

2.4 Engine Characteristics

For solving the equation between the needed and delivered torque at the propeller it is necessary to know the relation between torque and rpm of the engine at a certain steam or fuel inlet ratio.

In this connection two important types of engines for ship's propulsion are distinguished.

2.4.1 Turbine

Usually it is accepted that at an increasing engine loading and a constant engine setting the power remains constant. This means a hyperbolic relation between torque and number of revolutions:

$$Q = c \cdot h_m \cdot Q_0 \cdot \frac{n_0}{n}$$

According to some authors like Geisler and Siemer [13] and Goodwin et. al. [14] in practice there is a linear relation between torque and number of revolutions:

$$Q = c \cdot h_m \cdot Q_0 \cdot \left\{ a - (a-1) \cdot \frac{n}{n_0} \right\}$$

where the coefficient a depends on the type of the turbine:

$$a = 2.0 - 3.0$$

If one takes into consideration that the number of revolutions of the propeller of a ship in a sea-way will not reduce more than 10-15 percent at a constant steam inlet ratio, the assumption of a constant power is sufficiently accurate for calculating the ship’s speed. The relations between torque and rpm mentioned above are shown in figure 2.

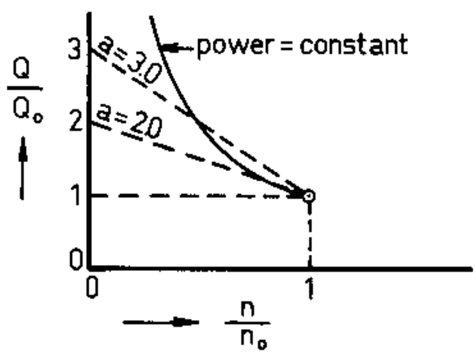


Figure 3 Torque – RPM Relation of a Turbine

2.4.2 Diesel Engine

For a diesel engine it is mostly accepted that at an increasing engine loading and a constant engine setting the torque remains constant. This means that $a = 1.0$ in the last equation and so:

$$Q = c \cdot h_m \cdot Q_0$$

In practice there is some difference with this assumption. At a constant engine setting and an increasing engine loading the torque will increase first, then obtains a maximum value and afterwards will decrease again. This can be approximated by a linear relation between torque and number of revolutions, provided that the number of revolutions will not reduce more than 10-15 per cent. Then the linear torque-rpm relation can be used with for instance $a = 1.5$. These relations between torque and number of revolutions are shown in Figure 3.

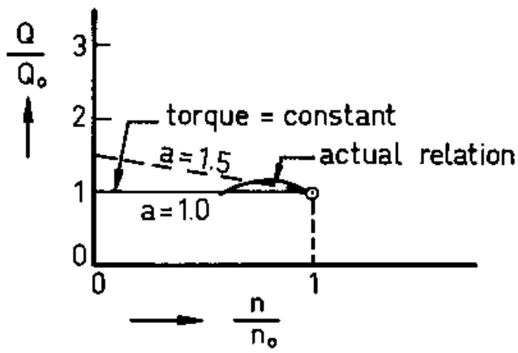


Figure 3 Torque-RPM Relation for a Diesel Engine

3 Calculation of Motions

The program TRIAL, mentioned before, calculates vertical absolute and relative motions in regular waves for different ship speeds. Ship motions in an irregular sea are determined by linear superposition of the ship responses to the individual regular wave components.

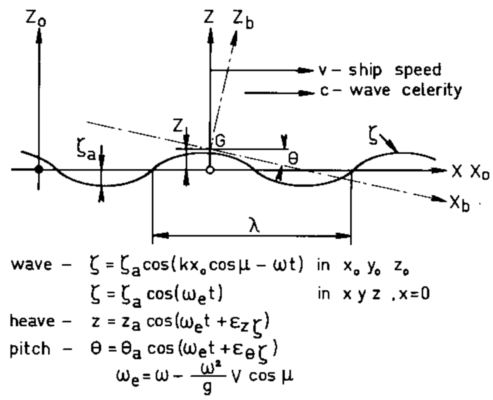


Figure 4 Symbols and Definitions

Let us consider the heave motion as an example for the calculating method. The definitions and symbols are shown in Figure 4.

In a complex notation the heave motion in regular waves can be written as:

$$z(t) = z_a \cdot \left| H_{zz}(w_e) \right| \cdot e^{i(w_e t + e_{zz})}$$

where

$$\left| H_{zz}(w_e) \right| = \frac{z_a}{z_a}(w_e)$$

defines the response function of the heave motion. The superposition principle enables the calculation of the variance of the heave motion in a known wave spectrum:

$$m_{0z} = \int_0^\infty S_z(w_e) \cdot dw_e$$

where

$$S_z(w_e) = \left| H_{zz}(w_e) \right|^2 \cdot S_z(w_e)$$

defines the heave spectrum.

For most practical applications it may be assumed that motion, velocity and acceleration amplitudes follow the Rayleigh distribution law. In this example the probability that the heave amplitude exceeds a certain value z_a^* is given by:

$$\Pr\{z_a > z_a^*\} = e^{\frac{-(z_a^*)^2}{2m_{0z}}}$$

The occurrence rate for this per hour will be:

$$N\{z_a > z_a^*\} = \Pr\{z_a > z_a^*\} \cdot \frac{3600}{2p \cdot \sqrt{\frac{m_{0z}}{m_{2z}}}}$$

in which the second moment of the heave spectrum is given by:

$$m_{2z} = \int_0^\infty S_{zz}(w_e) \cdot w_e^{\,2} \cdot dw_e$$

The significant amplitude of the heave motion is given by:

$$\bar{z}_{a1/3} = 2 \cdot \sqrt{m_{0z}}$$

In this way the program TRIAL calculates the significant amplitudes of heave, pitch, absolute and relative motions and accelerations and the probability and number per hour of exceeding a certain value by the relative motion.

3.1 Relative Motions

Neglecting the wave disturbance by the ship the relative motion at a longitudinal distance x_b from the centre of gravity is given by:

$$s = z_{x_b} - z + x_b \cdot q$$

where z_{x_b} is the vertical wave displacement at position x_b.

Significant amplitudes and probabilities of exceeding a given value are calculated as showed for the heave motion. Because of bow waves and sinkage due to the ship's speed, the effective freeboard f_e at the bow generally differs from the geometric freeboard f.

Tasaki [15] gives an empirical formula for this static swell-up at the bow:

$$\Delta f = f - f_e = 0.75 \cdot B \cdot \frac{L}{L_e} \cdot Fn^2$$

with L is the ship length and L_e is the length of entrance of the water line.

Experiments at the Delft Ship Hydromechanics Laboratory with a model of a fast cargo ship in full load and in ballast condition has shown a remarkably good agreement between the measurements and this empirical formula. For calculating the probability of deck wetness at the forward perpendiculars the geometrical freeboard is decreased with the static swell-up obtained from Tasaki's formula.

Generally, the probability of slamming will be calculated at station 17 or 18. It is assumed that the static swell-up at these stations is zero at the instant of re-entry of the forefoot in the water in case of slamming.

Dynamic phenomena increase the amplitude of the relative motion at the bow; there is a dynamic swell-up. When the bow immerses, the water surface will rise and when the bow emerges, the water surface will fall. Tasaki [15] has carried out forced oscillation tests with a towed ship model in still water to measure the displacement of the water surface relative to the bow of the model. From the results of these experiments he has obtained an empirical formula to estimate the dynamic swell-up at the bow:

$$\frac{\Delta s_a}{s_a} = \frac{C_b - 0.45}{3} \cdot \sqrt{\frac{L}{g}} \cdot w_e$$

with the restriction:

$$0.60 < C_b < 0.80$$

So the amplitude of the relative motion at the bow is:

$$s_a^* = s_a \cdot \left(1 + \frac{\Delta s_a}{s_a}\right)$$

This formula is used in the program for calculating the probability of shipping water at the forward perpendiculars.

Van Sluys and Tan have carried out experiments in regular waves [16] with compact frigates that have shown that the wave amplitude along the ship's hull is influenced by a factor between 0 and 2. The highest dynamic swell-up appeared in the neighbourhood of station 17 or 18. Also, experiments at the Delft Ship Hydromechanics Laboratory have shown here a dynamic swell-up of roughly double the value of the dynamic swell-up at the bow. For calculating the probability of slamming it is assumed that the dynamic swell-up at station 17 or 18 is double the value of Tasaki at the bow. More investigations are necessary to estimate a good mean value.

3.2 Accelerations

The absolute motion at a longitudinal distance x_b from the centre of gravity can be expressed in heave and pitch motions by:

$$v = z - x_b \cdot q$$

The response function of the absolute motion is:

$$\left|H_{vz}(w_e, x_b)\right| = \frac{v_a}{z_a}(w_e, x_b)$$

which also can be used for calculating the response function of the accelerations at position x_b by:

$$\left|H_{\ddot{v}z}(w_e, x_b)\right| = \left|H_{vz}(w_e, x_b)\right| \cdot w_e^2$$

The variance of the accelerations in a wave spectrum and the Rayleigh distribution gives the probability of exceeding a certain value by the amplitude of the acceleration:

$$\Pr\left\{\ddot{v}_a > \ddot{v}_a^*\right\} = e^{\frac{-\left(\ddot{v}_a^*\right)^2}{2m_{0\ddot{v}}}}$$

It is also possible to determine the probability of exceeding a certain value by the significant amplitude of the acceleration.
As Ochi and Motter have shown in [17], the probability expression:

$$\Pr\left\{\ddot{v}_{a1/3} > a\right\} \leq b$$

is the same expression as:

$$\Pr\left\{\ddot{v}_a \geq \frac{1}{2} \cdot a \cdot \sqrt{-2 \cdot \ln b}\right\} \leq b$$

This expression will be used in chapter 4.

4 Voluntary Speed Reduction

When a ship encounters a severe storm the ship’s captain will reduce speed in order to ease severe motions.

The most important phenomena for this decision are the probability of occurrence and severity of:

1. Deck wetness
   Caused by shipping water, this will happen if the relative motion of the bow exceeds the effective freeboard forward. The probability of deck wetness is expressed by:
   $$\Pr\{\text{deck wetness}\} = e^{\frac{-f_e^2}{2m_{0s}}}$$
   in which m_{0s} includes the dynamic swell-up.

2. Slamming
   Slamming is a phenomenon associated with extreme ship motions in waves. At certain ship speeds in rough seas, the forefoot of the ship emerges from the water as a result of large pitch and heave motions and violently impacts the water surface as it re-enters. The ship's forward bottom thereby sustains a heavy impulsive pressure from the water and this impulsive force produces a shudder throughout the hull.
   According to Ochi [18] the probability of occurrence of slamming is the joint probability that the bow emerges and that the relative velocity exceeds a certain magnitude at the instant of re-entry. He found a critical relative velocity between the bow and waves, below which slamming does not occur and recommends as a good threshold value:
   $$\dot{s}_{cr} = 0.093 \cdot \sqrt{g \cdot L}$$
   The probability of slamming is expressed by:
   $$\Pr\{\text{slamming}\} = e^{-\left(\frac{T^2}{2m_{0s}} + \frac{\dot{s}_{cr}^2}{2m_{0\dot{s}}}\right)}$$

in which m_{os} and $m_{0\dot{s}}$ include the dynamic swell-up.

3. Propeller racing
   The time-dependent immersion of the propeller results in a fluctuating torque and thrust of the propeller. Although the rpm governors greatly reduce possible damage to the propelling machinery due to racing, large torque and thrust fluctuations are observed in waves, even at constant rpm.
   Aertssen [19] analysed a lot of full-scale trials and defined for propeller racing: there is racing - or the propeller will be called emergent - on every occasion when the decrease of torque is in excess of 25 per cent. Neglecting a static and dynamic swell-up at the stern, Fukuda [22] has adopted occurrence of propeller racing when the propeller emergence exceeds one-third of the diameter of the propeller.

4. Accelerations
   Too high accelerations can also be a reason to reduce speed. The magnitude of the accelerations is strongly dependent on the ship's length. Aertssen [20] measured on the trawler "Belgian Lady" even accelerations of $2.75 \cdot g$ at the forward perpendiculars. Gerritsma showed the same in [21].

In [17] Ochi and Motter distinguish, for the estimation of a limit below which no voluntary speed reduction is expected, two loading conditions:

1. Full load condition

In this condition voluntary speed reduction is depending on deck wetness and accelerations at the bow:

$$\Pr\left\{\begin{bmatrix}\text{deck}\\ \text{wetness}\\ \text{at}\\ \text{Station } 20\end{bmatrix} \text{and/or} \begin{bmatrix}\text{sign. ampl.}\\ \text{of bow}\\ \text{acc. will}\\ \text{exceed}\\ 0.4 \cdot g\end{bmatrix}\right\} \leq 0.07$$

2. Light load condition
   Slamming at station 17 and bow acceleration are in this condition reasons for voluntary speed reduction.

$$\Pr\left\{\begin{bmatrix}\text{slam}\\ \text{impact}\\ \text{at}\\ \text{Station } 17\end{bmatrix} \text{and/or} \begin{bmatrix}\text{sign. ampl.}\\ \text{of bow}\\ \text{acc. will}\\ \text{exceed}\\ 0.4 \cdot g\end{bmatrix}\right\} \leq 0.03$$

Relative motion and velocity are both normal random processes, so they are treated as statistically independent.

For two statistical independent events A and B may be written:

$$\Pr\{A \text{ and/or } B\} =$$
$$= 1.0 - \Pr\{(\text{not } A) \text{ and/or } (\text{not } B)\}$$
$$= 1.0 - \Pr\{\text{not } A\} \cdot \Pr\{\text{not } A\}$$

So the probability function:

$$\Pr\{A \text{ and/or } B\} \leq c$$

may be written as:

$$\Pr\{\text{not } A\} \cdot \Pr\{\text{not } A\} \geq 1.0 - c$$

As mentioned in Section 3.2, the probability expression with significant acceleration amplitude can be expressed in the amplitude of this acceleration and the two criteria of Ochi and Motter can be expressed as follows:

- Full load condition:

$$\left(1 - e^{\frac{-f_e^2}{2m_{0s}}}\right) \cdot \left(1 - e^{\frac{-(0.4612g)^2}{2m_{0\ddot{v}}}}\right) \geq 0.93$$

- Light load condition:

$$\left(1-e^{-\left(\frac{T^2}{2m_{0s}}+\frac{\dot{s}_{cr}^{2}}{2m_{0\dot{s}}}\right)}\right)\cdot\left(1-e^{\frac{-(0.5296\cdot g)^2}{2m_{0\ddot{v}}}}\right)\geq 0.97$$

These two conditions are used in the program ROUTE

5 Practical Applications

In the following parts of this Chapter a description of the data input in the program is given with a discussion about sea and wind conditions. For six ships, calculation results are compared with full-scale measurements. The time used by an IBM 370/158 system, like that of the Mathematical Centre of the Delft University of Technology, for calculating speed and motions in a seaway is about two minutes for one loading condition with a memory use of about 400 Kbytes.

5.1 Description of Data Input

The program needs much information about the ship. To show this, the data input for a fully loaded ship is given here:

- text card with 80 symbols including spaces
- length at design waterline
- length between perpendiculars
- distance from ordinate zero until APP
- ratio between gyradius and length between perpendiculars
- estimated service speed
- even number of ordinate intervals
- even number of waterline distances
- number of wave and wind directions
- number of points for which relative motions will be calculated
- number of wave spectra and wind speeds
- number of power inputs
- array with ordinate distances from ordinate zero until forward
- from ordinate zero until forward, for every ordinate:
    - ordinate number
    - array with half widths of the section at the waterlines from keel until load waterline
    - array with waterline distances of the section from keel until load waterline
- array with positions with respect to ordinate zero of the points for which relative motions, shipping water, slamming and acceleration forward will be calculated
- array with z-values for calculating the probability of exceeding, shipping water and slamming (above load waterline is positive)
- array with wave directions (head waves is 180 degrees)
- array with absolute wind directions (head wind is 180 degrees)
- array with significant wave heights
- array with average wave periods
- array with absolute wind speeds
- length overall
- lateral projected wind area
- transverse projected wind area
- length of perimeter of lateral projected wind area excluding waterline and slender bodies such as masts and ventilators
- number of distinct groups of masts or king posts seen in lateral projection
- type of estimation method of the still water resistance:
    - 1 = method of Lap and Auf 'm Keller
    - 2 = method of Shipbuilding Research Association of Japan
- multiplication coefficient for correcting the calculated still water resistance for a bulbous bow, fouling, etc
- type of estimation method of the wake fraction:
    - 1 = method of Taylor
    - 2 = method of Harvald
    - 3 = a given value of w
- if type = 3 : value of w

- type of estimation method of the thrust deduction fraction:
    - 1 = method of Weingart
    - 2 = a given value of t/w
    - 3 = a given value of t
- if type = 2: value of t/w
- if type = 3: value of t
- relative rotative efficiency
- number of propellers
- number of propeller blades
- diameter of propeller
- blade area ratio
- pitch ratio
- boolean: English horsepower (1 hp = 76 kg m/sec)
- for every input of power:
    - type of machine:
      1 = power is constant
      2 = torque-rpm is linear
    - steam or fuel inlet ratio
    - mechanical efficiency of the shaft bearings
    - power in design condition
    - rpm in design condition
    - if type = 2 : linear coefficient of torque-rpm relation
- boolean: ballast condition
- if this boolean is true:
    - change of draught at ordinate zero
    - change of draught forward
    - ratio of gyradius and length between perpendiculars.

The dimensions of the different values are:

length:	meter
time:	second
speed:	knots
power:	horsepower
angle:	degree

5.2 Sea and Wind Conditions

The recommendations of the twelfth I.T.T.C., Rome, 1969, are used for the description of sea and wind conditions.
The wave spectra are defined by:

$$S_z(w) = \frac{A}{w^5} \cdot e^{\frac{-B}{w^4}}$$

in which:

w	wave frequency and
A, B	coefficients.

If statistical information is available on the characteristic wave period $\bar{T}$ and the significant wave height $\bar{H}_{1/3}$, a two-parameter spectral formulation can be used by defining:

$$A = \frac{173 \cdot \bar{H}_{1/3}^{\,2}}{\bar{T}^4} \quad \text{and} \quad B = \frac{691}{\bar{T}^5}$$

in which:

$$\bar{H}_{1/3} = 4 \cdot \sqrt{m_0}$$

$$\bar{T} = 2p \cdot \sqrt{\frac{m_0}{m_2}}$$

This period is based on the spectral centre of gravity and it can be taken as the observed period. The spectral formulation, mentioned above, is used in the program.

If the only information available is the significant wave height, the 12th ITTC recommends for the coefficients A and B:

$$A = 0.78 \quad \text{and} \quad B = \frac{3.11}{\bar{H}_{1/3}^{\,2}}$$

This means in the two-parameter spectral formulation a relation between significant wave height and characteristic wave period:

$$\bar{T} = 3.86 \cdot \sqrt{\bar{H}_{/3}}$$

The 12th ITTC also recommends a relation between wind speed and significant wave height in an open ocean when no data are available:

V_W (kn)	$\bar{H}_{1/3}$ (m)
20	3.05
30	5.25
40	8.10
50	11.15
60	14.65

5.3 Calculations and Full Scale Measurements

For six ships calculation results of program ROUTE are compared with full-scale measurements: 4 ships with a diesel engine and 2 ships with a turbine propulsion plant. The main dimensions of these ships are shown in Table 1.

Only measurements in head waves ($150^0 \leq m \leq 180^0$) are observed to compare them with calculations of the behaviour of these ships in head wind and waves (180^0).

In calculating the wave spectra the relation between significant wave height and average wave period is defined by:

$$\overline{T} = 3.86 \cdot \sqrt{H_{1/3}}$$

as mentioned before. The corresponding wind speed as recommended by the twelfth I.T.T.C. is used.

It may be noted that differences between predictions and measurements, apart from possible disagreements between theory and practice, can be caused by different reasons. All measurements have a certain error depending on measuring techniques and accuracy of the measuring equipment. There is always a difference between the actual wave spectrum and the wave spectrum derived from a spectral formulation with a measured, estimated or assumed significant wave height and average wave period. The input values in the program, like engine setting corresponding to a certain torque or power, wave direction, wind direction and wind speed are mean values. Deviations from these mean values result in differences between predicted and measured behaviour of the ship.

name		Lukuga	Lubumbashi	Jordaens	Dart Europe	Atlantic Crown	Kelletia
length between perpendiculars	m	136.00	136.00	146.15	218.00	196.00	161.55
breadth	m	18.70	18.70	20.10	30.48	28.00	21.11
mean draught	m	8.78	7.87	8.53	9.14	8.15	9.05
trim by stern	m	0.30	0.08	0.06	0.00	0.00	0.00
weight of displacement	t	16308	14401	17716	37603	26579	24785
block coefficient		0.708	0.697	0.690	0.603	0.576	0.778
service speed	kn	16	15	16.5	21.0	23.0	14.5
number of propellers		1	1	1	1	2	1
type of engine		diesel	diesel	diesel	diesel	turbine	turbine
B.H.P.		7400	6000	9000	29000		8250
r.p.m.		115	112	119			103
Medium or light load condition							
mean draught	m	5.72	5.84	7.01	7.93	-	-
trim by stern	m	1.49	1.68	0.09	1.24	-	-
weight of displacement	t	10032	10300	14159	31987	-	-

Table 1 Main Dimensions of Comparing Ships

Firstly the calculation results for the four ships with a diesel propulsion plant will be discussed and after that the results for the two ships with turbine propulsion plant.

In the last two decades, Aertssen has carried out experiments with several ships to study the behaviour of these ships in a seaway. The measurement results of 4 ships are used to compare them with the predictions in head waves:

m.s. Lukuga [23]
m.s. Lubumbashi [24, 25]
m.s. Jordaens [19]
m.s. Dart Europe [26].

The first three ships are conventional cargo liners and the last one is a containership, all owned by the Compagnie Maritime Belge in Antwerp, Belgium.

Aertssen gives in his papers much information and data. The following are used to compare them with the predictions: power delivered at the propeller, number of revolutions per minute of the propeller, speed, significant wave height and the significant amplitudes of pitch and heave motions and vertical bow acceleration.

For m.s. Lukuga, m.s. Lubumbashi and m.s. Jordaens, the increase of power due to fouling is assumed to be 8 per cent of the power in still water at the same speed. In calculating the still water resistance of m.s. Dart Europe no allowance is made for the bulbous bow, so it is assumed that increase of power due to fouling will be nullified by decrease of power due to a bulbous bow.

In order to get a good comparison it is necessary to use the actual torque-rpm relation in the calculations. Figure 5 shows these relations for the torque measured at the propeller. Those measurements are divided into groups having broadly the same torque. Assuming a constant torque at a constant engine setting, this means groups of a constant engine setting. For a torque equal to the torque derived from the break horsepower of the engine and a maximum rpm belonging to it, the engine setting is assumed to be 100 per cent.

The comparison between predictions and measurements are shown in Figures 6, 7, 8 and 9. The predicted speeds are in reasonably good until very good agreement with the mean values of the measurements. In rough seas however the predicted speeds are a little bit too low, but the measurement points scatter more than two knots. The predicted number of revolutions is somewhat too high; in mild weather conditions even higher than the maximum value limited by the governor of the engine. Figure 11 shows that this can partly be caused by the estimated wake and thrust deduction fraction. Another reason can be a possible difference between the characteristics of the actual propeller and the characteristics of the Wageningen B-series propeller used in the calculations. The predicted significant amplitudes of pitch and heave motions and vertical bow accelerations are in good agreement with the measurements by Aertssen.

The calculated limits of speed and significant wave height for voluntary speed reduction due to the two criteria of Ochi and Motter are also plotted in the Figures 6, 7, 8 and 9. There was no bad weather in head seas during the experiments of m.s. Lukuga in full 1oad condition and m.s. Lubumbashi in both loading conditions. The criteria could not be checked in these cases.

The criterion for full load condition (in the Figures marked by SH) with a maximum probability of shipping water and exceeding $0.4 \cdot g$ by the significant amplitude of the bow acceleration of 7 per cent, seems to be too low for m.s. Jordaens and m.s. Dart Europe.

The criterion for light load condition (in the Figures marked by SL) with a maximum permitted probability of slamming and exceeding $0.4 \cdot g$ by the significant amplitude of the bow acceleration of 3 per cent, appears also to

be too low. The criterion valid in full load condition seems to be better here. More investigations are necessary to get good mean values for these percentages used in the program.
The predictions of this computing method are also compared with measurements on turbine ships. In 1972 Beukelman and Buitenhek carried out experiments on the containership Atlantic Crown [27]. In the calculations it is assumed that the still water resistance of this twin-screw ship with a bulbous bow, including fouling, is equal to the still water resistance calculated by the method of the Shipbuilding Research Association of Japan for single-screw ships with a conventional bow, excluding fouling. The agreements between predictions and measurements of speed, number of revolutions and pitch and heave motions are very good as is shown in Figure 10.
The routing office of the Royal Netherlands Meteorological Institute made speed loss graphs available for a group of turbine ships. For one of these ships, t.s. Kelletia, predictions are made in full load condition. The increase of power due to fouling is assumed to be 8 per cent of the power in still water at the same speed. The predictions and observations are shown in Figure 10. Maximum observed speeds are in good agreement with the predicted speeds at 7500 horsepower. The maximum continuous number of revolutions of the propeller, 100 rpm, is in very good agreement with the predicted value.

6 Final Remarks

The calculation of the three components of the total resistance and the speed of a ship, at a constant engine setting in a seaway, shows in Figure 12 for m.s. Lubumbashi that added resistance due to waves can be a considerable part of the total resistance. At a significant wave height corresponding with Beaufort 6 the added resistance is equal to the still water resistance. Of course this is depending on the ship's length.
In designing a ship, much attention will be paid to the still water resistance in relation to bull form and expensive bulbous bows. On the North Atlantic however, a sea state of Beaufort 6 is exceeded in 70 per cent of the time during the winter season. In the summer season this percentage is 45 [21]. Considering this, it is worth while to pay more attention to added resistance and motions in a seaway.
The program ROUTE can be an expedient for investigating this problem. This program can be made suitable for calculating the fuel consumption of a ship in a seaway after which it can be used for routing a ship with a minimum use of fuel, predictions of fuel consumption, etc. Except for routing purposes, this program can be used for the determination of needed machine power at a service speed in a certain state and choice of a propeller in the regular design procedure of a ship, in lengthening of ships, etc. In the near future this program will also be made suitable for following waves.

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9 List of Symbols

R_{SW}	still water resistance
R_W	wind resistance
R_{AW}	added resistance due to waves
R_T	total resistance
T	trust of the propeller
Q	torque at the propeller
Q_m	torque at the engine
Q_0	torque at the engine (design maximum)
n	number of revolutions
n_0	number of revolutions (design maximum)
a	coefficient for the torque-rpm relation
P	power
V_a	speed of advance
V	ship's speed
t	thrust deduction fraction
w	wake fraction
V_W	true wind speed
a_W	true wind direction
$\overline{H}_{1/3}$	significant wave height
$\overline{T}$	average wave period
m	wave direction
c	steam or fuel inlet ratio
h_m	mechanical efficiency of the shaft bearings
K_T	thrust coefficient
K_Q	torque coefficient
r	density of water
D	diameter of propeller
J	advance coefficient
h_R	relative rotative efficiency
L	length
B	breadth
T	draught
C_b	block coefficient
C_{wp}	water plane coefficient
q	pitch motion
z	heave motion
v	absolute vertical motion
$\ddot{v}$	vertical acceleration
s	relative vertical motion
x_b	longitudinal distance to centre of gravity
z_a	wave amplitude
w_e	frequency of encounter
$S_{..}$	spectral value
$m_{..}$	variance or spectral moment
f	geometric freeboard
f_e	effective freeboard
$\Pr\{\ \}$	probability
g	acceleration of gravity
w	circular wave frequency

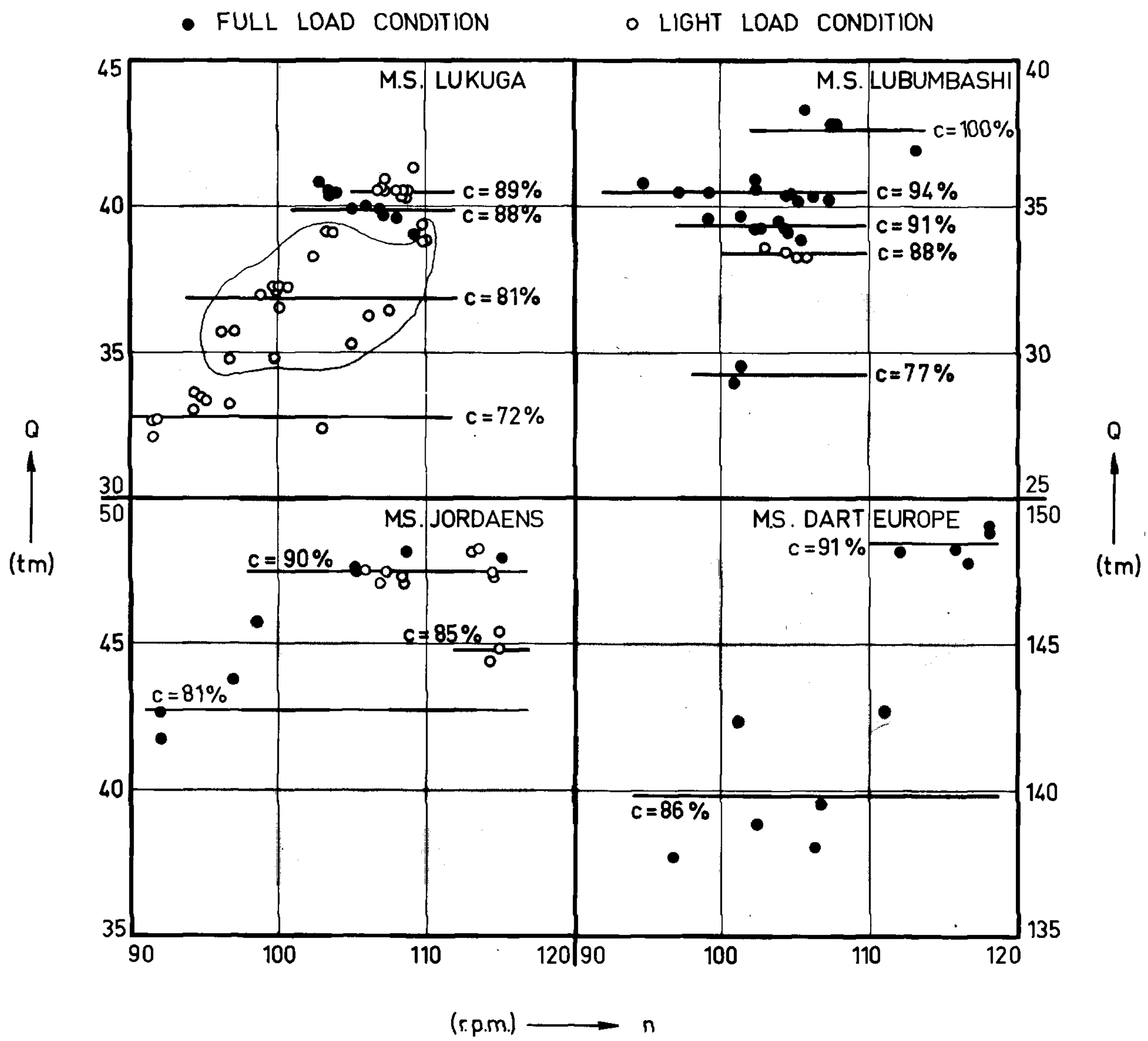

Figure 5 Measured and Assumed Torque-RPM Relation for Diesel Propelled Ships

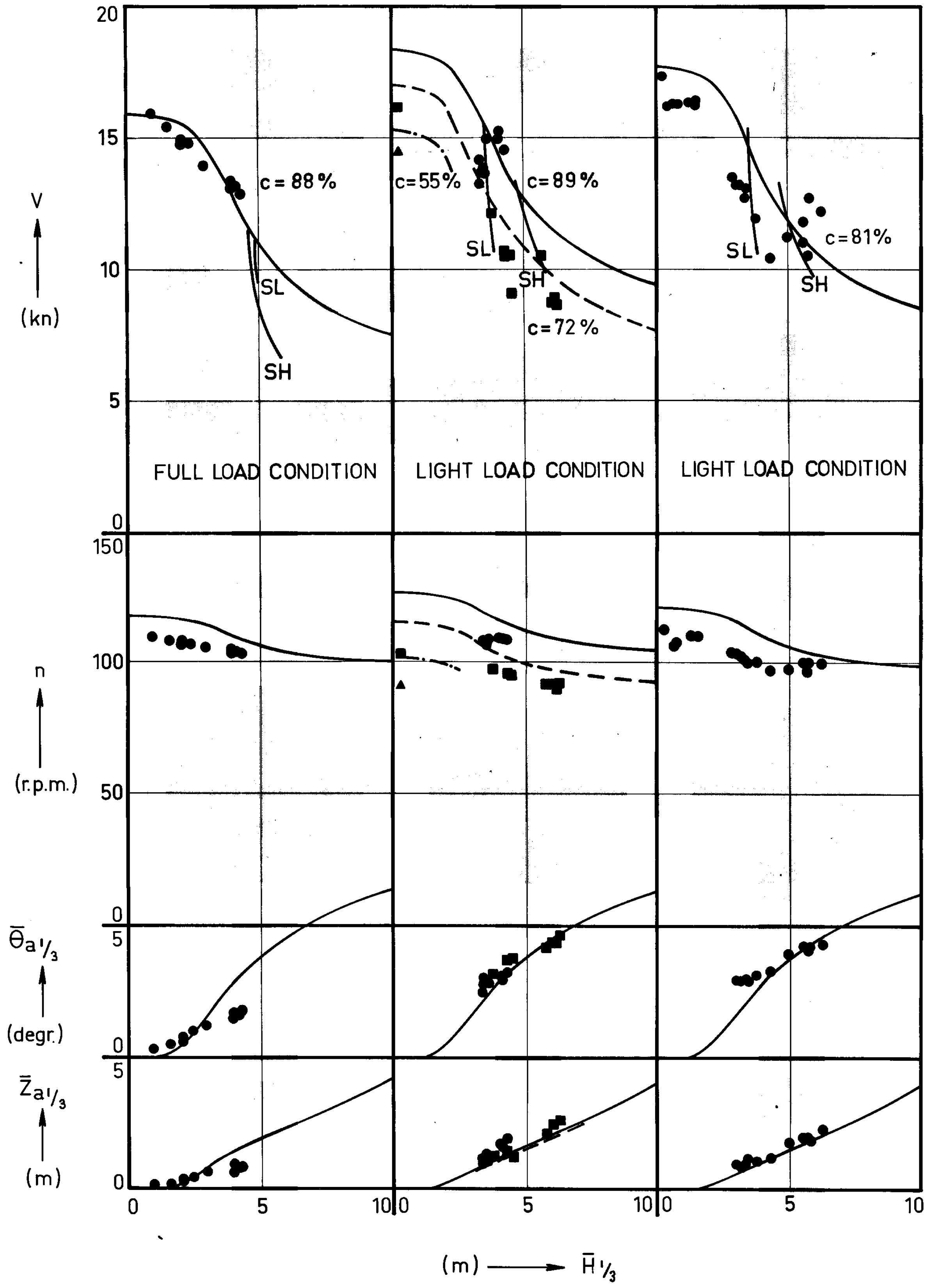

Figure 6 Predicted and Measured Behaviour of m.s. Lukuga in a Seaway (Head Waves)

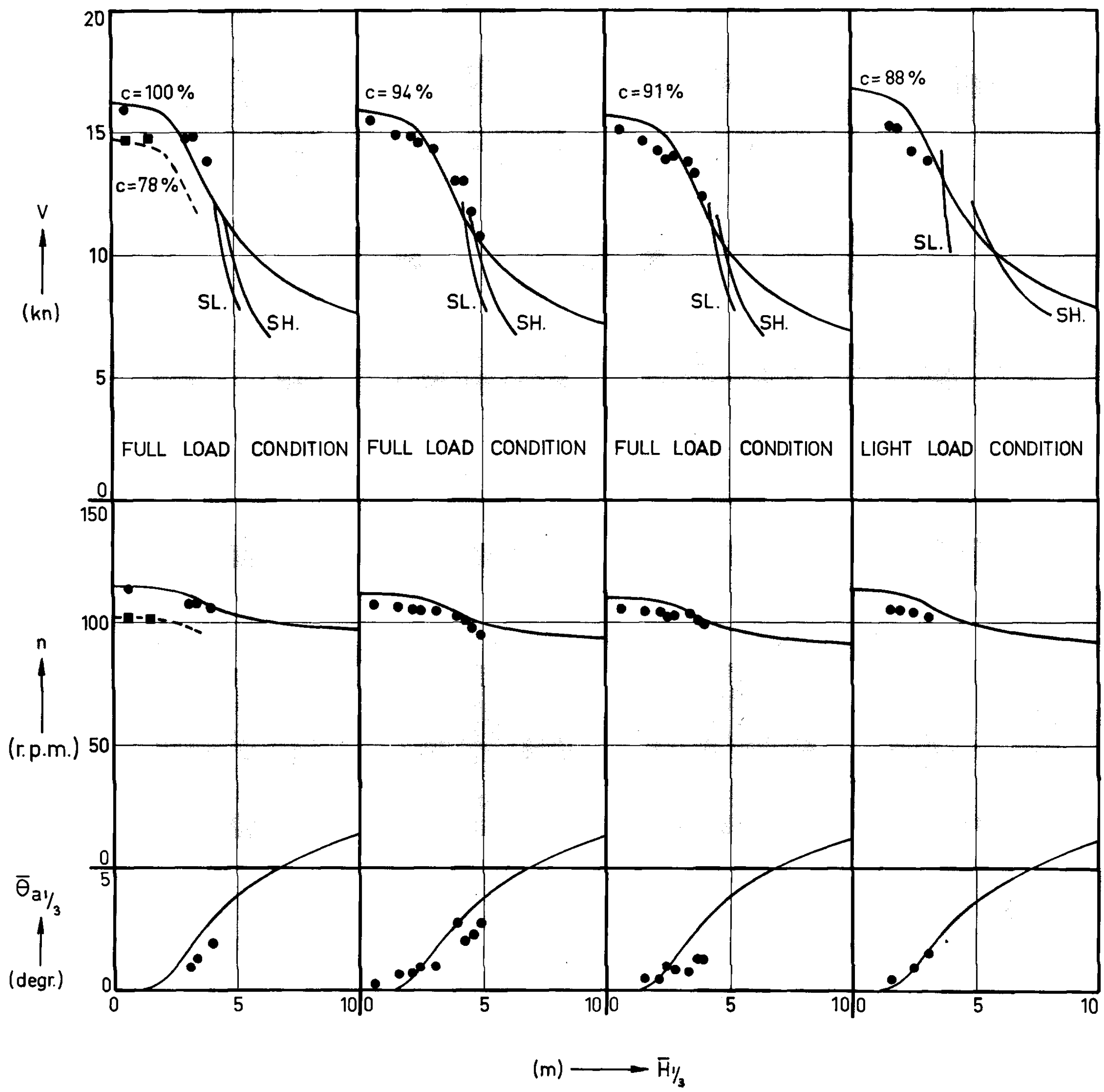

Figure 7 Predicted and Measured Behaviour of m.s. Lubumbashi in a Seaway (Head Waves)

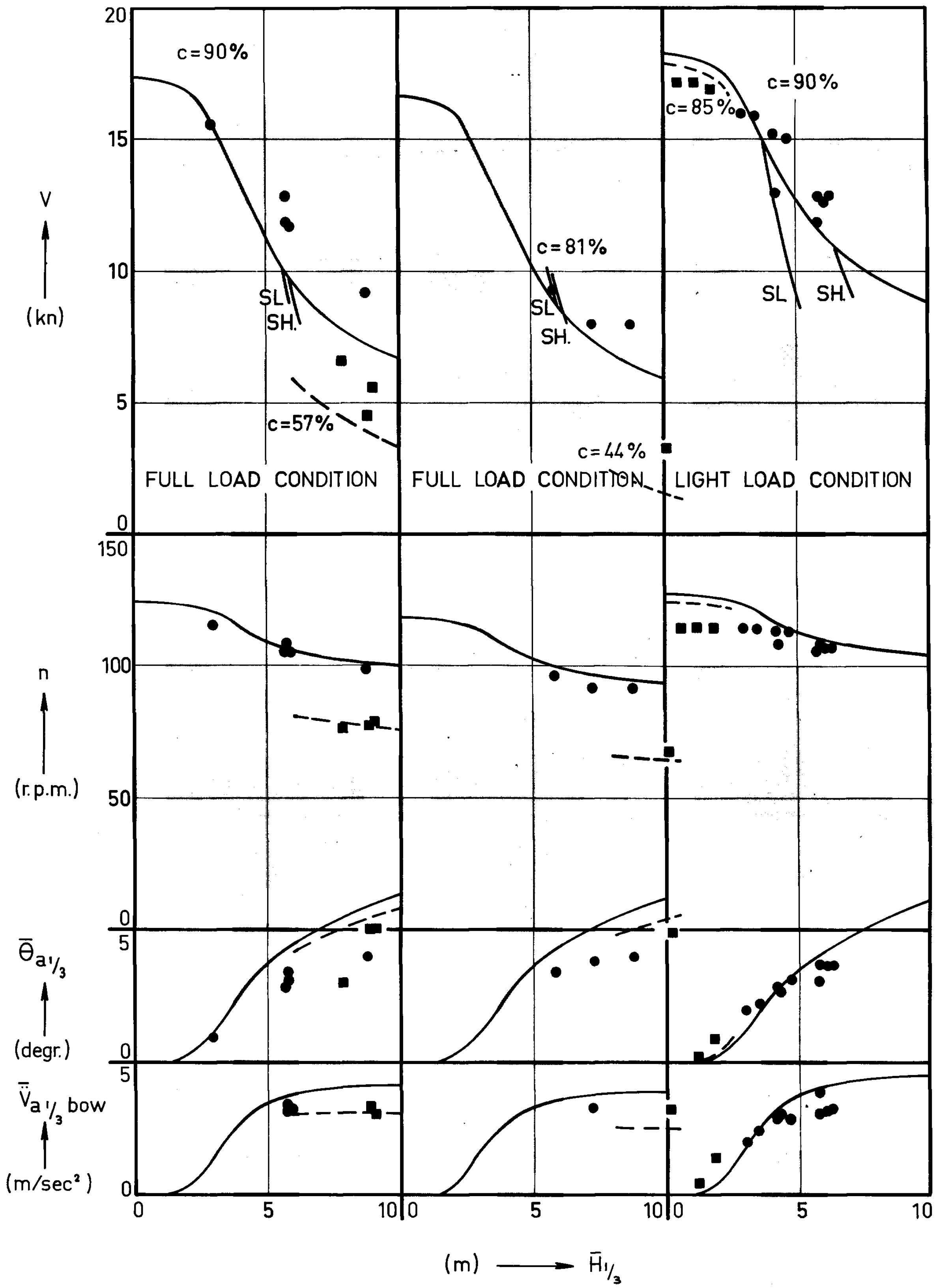

Figure 8 Predicted and Measured Behaviour of m.s. Jordaens in a Seaway (Head Waves)

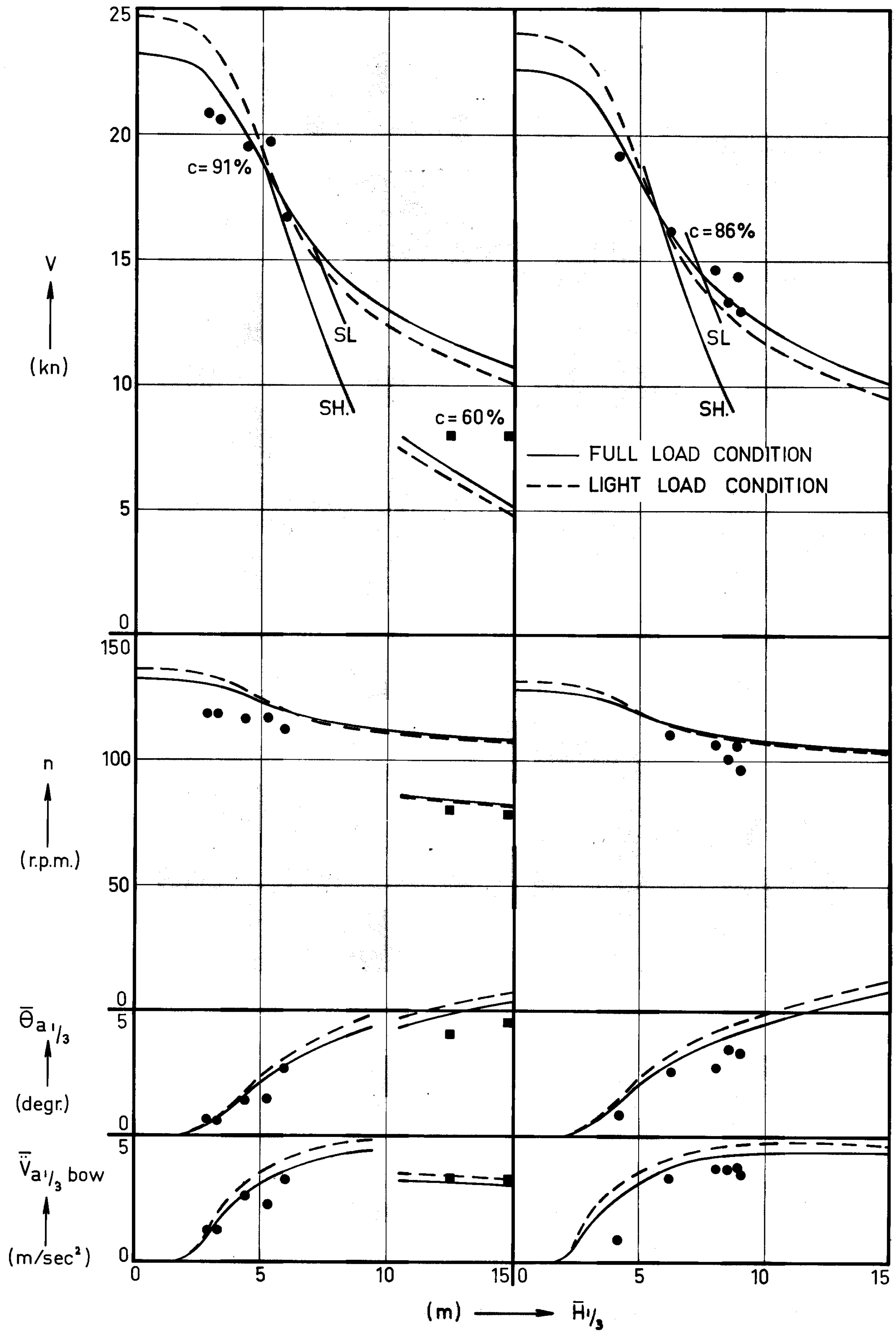

Figure 9 Predicted and Measured Behaviour of m.s. Dart Europe in a Seaway (Head Waves)

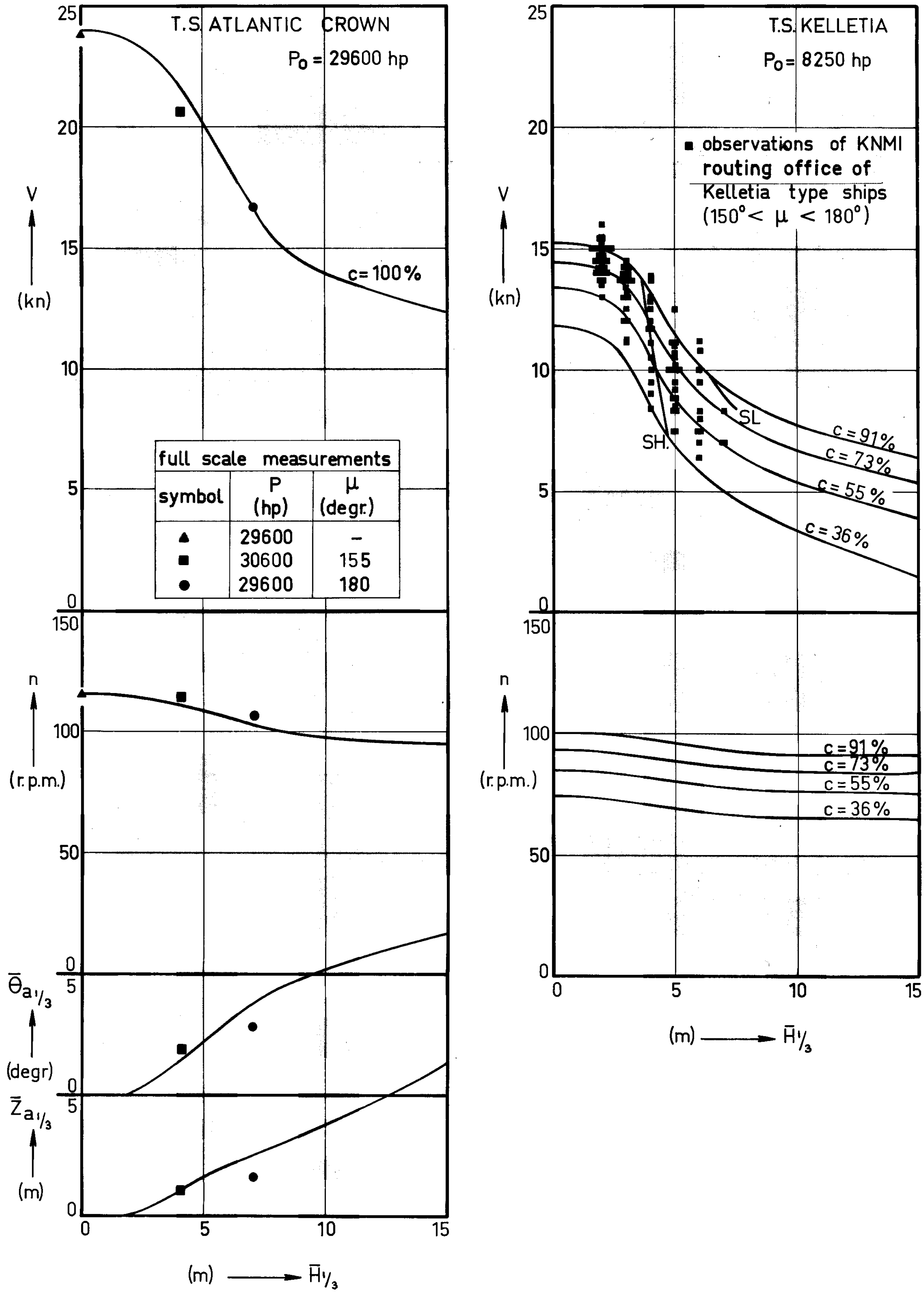

Figure 10   Predicted and Measured Behaviour of 2 Turbine Ships in a Seaway (Head Waves)

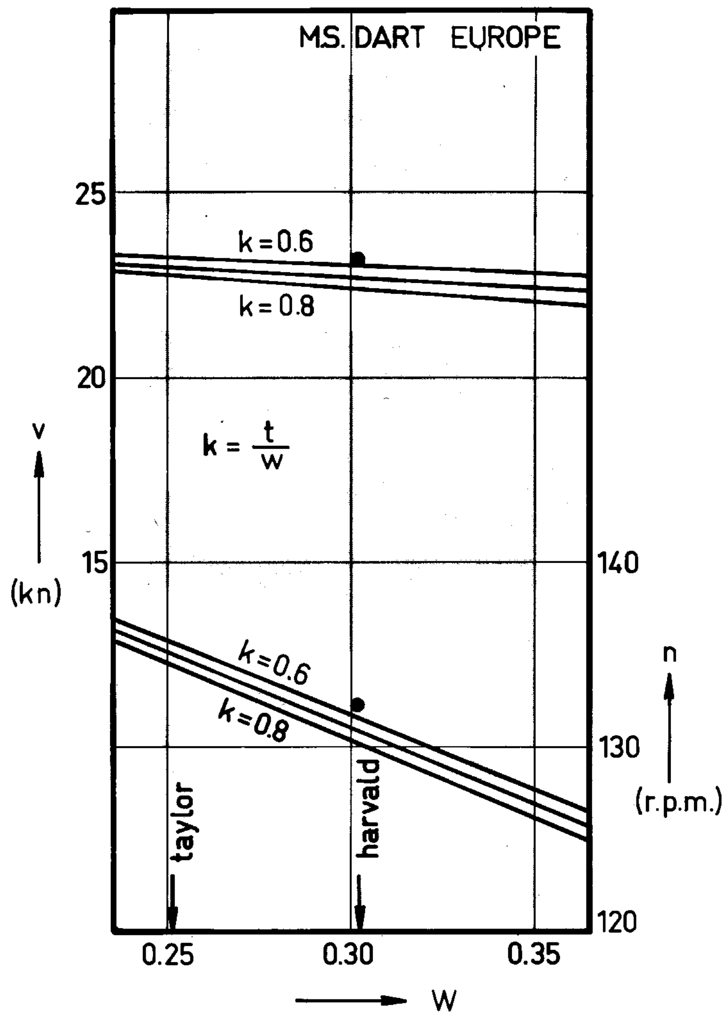

Figure 11 Influence of Estimated Wake and Thrust Deduction Fraction on Calculated Speed and RPM

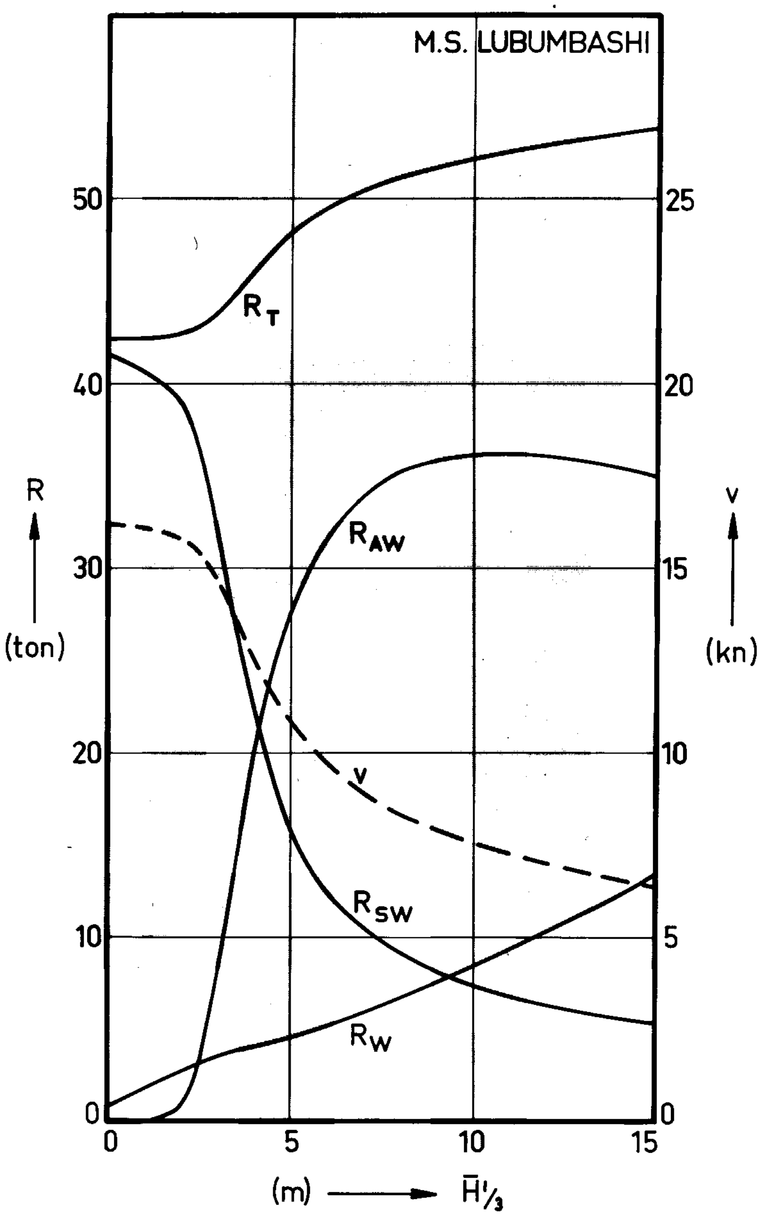

Figure 12 Division of the 3 Components of Total Resistance at a Constant Engine Setting of a Ship in a Seaway (Head Waves)