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1- "Structural and Economical Consequences of Ship Deflection", Seminar on the Application of Science & Technology in Marine Transport, A.M.T.A., J. Res. and Consultation Centre, July. (Egypt-1974), Shama, M. A.,

2- "Optimizing Hull Steel Weight for Overall Economic Transportation", Marine Week, May 2, (UK-1975), Shama, M. A.,

3- "The Cost of Irrationality in Ship Structural Design", PRADS. Int. Conference on Practical Design in Shipbuilding, SNAJ, Tokyo Oct. (Japan-1977), Shama, M. A.,

4- "Computer Design of Ships", Bull. Collage of Engineering, Basra University, (Iraq-1977), Shama, M. A.,

5- " Economical Consequences of Irrational Structural Design of Ships", Bull. Of Collage of Eng., Basra University, Vol.2, No.1, March, (Iraq-1977), Shama, M. A.,

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7- "ON the Economics of Safety Assurance" Dept. of Naval Architecture and Ocean Engineering, Glasgow University, (UK-1979) Shama, M. A.,

8- "CADSUCS, the Creative CASD for the Concept Design of Container Ships", AEJ, Dec. (Egypt-1995), Shama, M. A., Eliraki, A. M. Leheta, H. W. and Hafez, K. A.,

9- "On the CASD of Container Ship; State of the Art", AEJ, Dec., (Egypt-1995) Shama, M. A., Eliraki, A. M. Leheta, H. W. and Hafez, K. A.,

10- "Assessment of Uncertainties of the Sea Margin", Maritime Research Journal, Sept., (Egypt-1998), Shama, M. A., Moniem, A. F. A. and Eweda, S.,

Assessment of uncertainties of the sea margin

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Abstract:

The objective of this work is to develop a method to predict the effect of random change of environmental conditions on the value of the sea margin in a seaway. The proposed method is based on a system engineering approach, and making use of available theoretical and experimental data. The matching procedure between the component parts of the propulsion system is discussed. The effect of marine environment on the encountered added resistance is considered. Accordingly, a tool is provided to predict the power needed to propel a ship with a certain speed in the early stages of ship design in a seaway. The importance of such tool, especially in the early stages of ship design, is clearly justified.

Keywords: Marine Diesel propulsion system, Added resistance, and sea margin.

1. Introduction:

The ship, in its lifetime, will meet many uncertainties, such as; the random changes in sea state, loading condition, port time, fouling growth rate, trading zone, fuel prices... etc. These uncertainties affect considerably the ship's propulsive performance.

A perusal of the available literature [1 to 8] indicates that some researchers provide incomplete treatment of the problem of estimating the propulsive performance of a ship and depends on calculated ship motions. The others deal with specific areas and do not provide reliable tool to the ship designer. Furthermore, it is noted that the effect of operational pattern on the propulsive performance of a merchant ship is not considered seriously. Therefore, the need for additional work in this area cannot be overemphasized.

2. Sea margin

The successful design of a ship depends, ultimately, on how the propulsive performance is calculated. Reflecting the random changes in the marine environment and the operational pattern on the propulsive performance of a ship is a complicated problem of stochastic nature. Hence, the naval architecture is usually forced to follow the traditional design procedure. Following that procedure, the propulsion power required to maintain the ship's service average speed under the influence of the environment prevailing in a seaway, is usually determined from still water resistance and allowing for mean service allowance. This allowance, sea margin, ranges between 15 to 30 percent as shown in Fig. (1)[1].

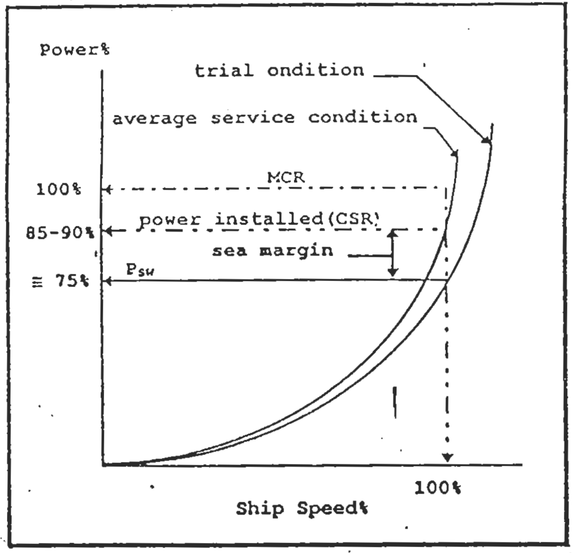


Fig. (1)
Power-Speed relationship,
illustrating sea margin.

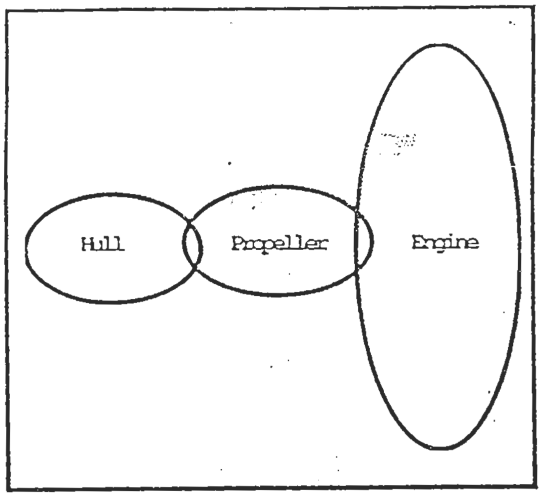


Fig. (2)
Ship's propulsion system

From the system engineering point of view, the propulsion system of any ship is considered to be composed of three subsystems, namely; hull, propeller and prime mover(s) subsystems as shown in Fig. (2). The hull performance may be defined as the total resistance encountered by the ship in a seaway. The performance of the propeller is usually defined by its efficiency of transforming the delivered prime mover(s) torque into thrust. The performance of a diesel engine is defined as the torque developed by the prime mover(s) at certain fuel rack position and engine speed (rpm). Accordingly, matching the three subsystems together is of crucial importance[2, 3].

For a propulsion system of a constant torque diesel engine as a prime mover, the matching procedure between hull and propeller as well as between engine and propeller is described as follows:

2.1 Hull-propeller matching

As it is well known, the propeller thrust decreases as the speed of its advance increases. Whereas, the water resistance of hull motion increases as the ship speed increases, the ship will reach a dynamic equilibrium when the two applied forces; resistance and thrust balance each other. Then:

$$R = T(1-t) \qquad (1)$$

Where :

R = total resistance, in kN.
T = thrust of propeller, in kN.
T = thrust deduction factor.

From Fig. (3), it is clear that the condition of dynamic equilibrium is changing randomly.

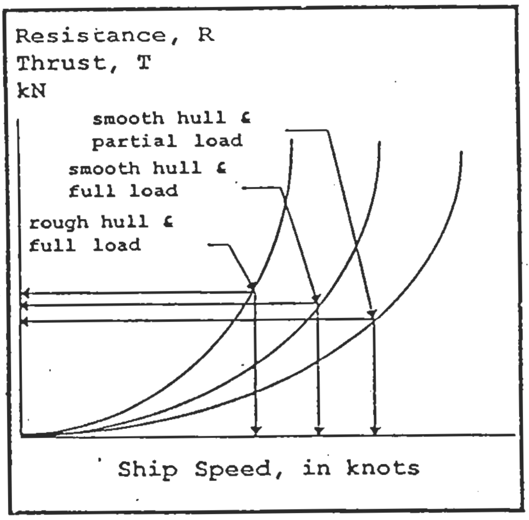


Fig. (3)
Hull-propeller matching

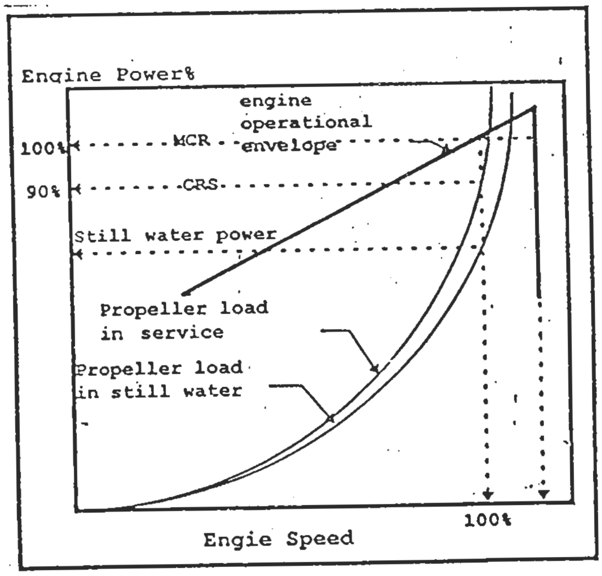


Fig. (4)
Engine-propeller matching

2.2 Propeller-engine matching

The dynamic equilibrium of the propeller-engine subsystems is achieved at the moment of equivalence of the torque developed by the engine and that absorbed by the propeller.

This equilibrium occurs at a certain engine speed, rpm, for a certain position of fuel rack and brake mean effective pressure; P_{mean} , as shown in Fig. (4). It is apparent that the equilibrium point changes randomly. Therefore, the power needed to maintain ship speed within the variable environment is not a fixed quantity.

To achieve an optimum matching between hull, propeller and engine; the engine power should be adequate enough to maintain the ship speed in a seaway.

3. Marine environment

Marine environment is usually defined by the following parameters; wind, waves, currents and fouling growth rate. For this work, marine environment will be defined by sea state (wind and waves) and fouling growth rate.

3.1 Wave spectra

The choice of an appropriate wave spectrum S (w), to represent a seaway, is an important task in the process of the prediction of added resistance. Since real sea conditions offer a wide variation in the shape of the sea spectra, small changes in a sea spectrum can result in a significant variation in the integrated average added resistance. These variations are due to the relative positions of the spectral peaks. Tejsen storm et al(4) investigated the effect of the shape of sea spectrum on the value of the added resistance. They concluded the significant effect of sea spectrum on the predicted values of added resistance.

The shape of wave spectra observed in the oceans varies considerably even though the significant wave height is the same. Therefore, to include all variations in spectral shapes that the ship may encounter in a seaway, it is necessary to use a systematic series of wave spectra. These systematic series consist of several members, called a family of wave spectra, for each sea state.

The idea of expressing wind generated waves' spectra in terms of two parameters were first introduced by Bertschneider[5, 6], and modified by Ochi[7, 8] as a function of the significant wave height and wave period as follows:

$$s(\omega) = 0.3125 \frac{\omega_m^4}{\omega^5} HS^2 e^{-1.25(\omega_m/\omega)^4} \qquad (2)$$

To apply the two-parameter wave spectrum for predicting the added resistance due to waves, it is necessary to specify the values of the modal frequency ω_m, for each sea condition. In a seaway, the magnitudes and number of occurrence of modal frequency, ω_m, in any sea region, are random. Therefore, the statistical data on wave height and period are necessary to determine the modal frequency in a given sea region. Wave statistics given by Hogben and Lumb[9], are extremely valuable for this purpose.

3.2 Wind

The strength of wind is classified, sometimes, by the Beaufort Scale, which is related to the wind speed as shown in Table (1) and Fig. (5)[10].

In Baeufort Scale there is a correspondence between wind speeds and significant wave heights. Therefore, wind speeds may be related to significant wave height via the following empirica formula:[11]

$$U = 3.2\ HS^{1.168} \exp - 0.064\ HS \qquad (3)$$

Where :

U = wind speed, in knots.

HS = significant wave height in m.

Table (1)

Beaufort number	Description of wind	Wind speed (knots)
0	Calm	0-1
1	Light air	2-3
2	Light breeze	4-7
3	Gentle breeze	8-11
4	Moderate breeze	12-16
5	Fresh breeze	17-21
6	Strong breeze	22-27
7	Moderate gale	28-33
8	Fresh gale	34-40
9	Strong gale	41-48
10	Whole gale	49-56
11	Storm	57-65
12	Hurricane	More than 65

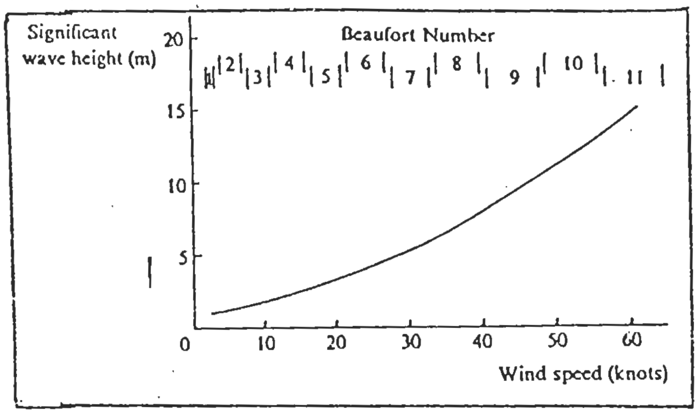


Fig. (5) : Dependence of the significant wave height on wind speed and Beaufort Scale

4. Added resistance

The added resistance is defined as the increase in the encountered resistance by any ship rather than still water resistance. In a seaway, the added resistance may be divided into three components; added resistance due to waves added resistance due to wind and added resistance due to hull roughness.

4.1 Added resistance due to waves:

As the ship goes on in sea waves, it experiences an average pressure force opposing its forward motion. This is called added wave resistance. This type of resistance is strongly dependant on the relationship between ship dimensions and wave parameters. Different approaches have been developed [12 to 22] to calculate the added resistance encountered by a ship in a seaway at different headings. In the present work, head sea is considered, since it represents the case of maximum added resistance.

In the literature, the added resistance in a seaway is calculated by the following equation:

$$R_{AWI} = 2\int_0^\infty S(\omega)\,\frac{R_{AW}(\omega)}{\varsigma^2}\,d\omega \qquad (4)$$

Where :

$S(\omega)$ = Wave spectrum, in $m^2.s$

R_{AW} = Average resistance increase in regular waves, in N.

ς = Wave amplitude, in meters.

ω = Wave frequency, in rad/s.

In order to calculate the added resistance due to sea waves (irregular waves) the formulae developed by V. Jinkine and Ferdinande [31] are used. V. Jinkine and Ferdinande formulae were chosen because of the following two reasons. The first is that it is based on model experiments as well as full scale trials for fast cargoships. while the second is that, it provides reasonable accuracy compared with available analytical tools.

4.2 Added resistance due to hull roughness

The roughness of the wetted hull surface of a ship in service is changing randomly, since the main contributors to such roughness are time dependent. These main contributors are found to be; original plate roughness, types and quality of paints/coatings, corrosion and fouling. The magnitude of each of these roughness components varies according to some specific parameters.

To estimate the resistance that accounts for the hull roughness, the equation adopted by the ITTC, 1978 [24], and modified by R. L. Townsin et al [25] is used:

$$\Delta C_f = 0.044\left[\left(\frac{MAA}{L}\right)^{1/3} - 10\left(R_n\right)^{-1/3}\right] + 0.000115 \qquad (5)$$

Where :

MAA = roughness mean apparent amplitude, in m.

ΔC_f = the increase in frictional resistance coefficient due to hull roughness.

L = ship's length, in meters.

R_n = Reynolds number.

$= \frac{VL}{\nu}$

V = Ship' speed in m/sec.

ν = Kinematics viscosity, in m^2/sec.

This equation was empirically derived based on BSRA data obtained through a series of full-scale tests performed on a group of ships. It accounts also for the effect of the ship's speed on the resistance encountered due to hull roughness. The total Mean Apparent Amplitude (MAA), is used to estimate the hull roughness effect on resistance. The value of MAA is calculated as given in appendix.

4.3 Added resistance due to wind:

In fact the wind resistance presents appreciable part of the total resistance in bad weather, especially for ships with large above water part; like container ships for example. Some formulae were developed over the last two decades for estimating wind resistance. However, most of these formulae did not cover the whole range of merchant ships [26 to 31].

R. M. Isherwood [40] used the regression analysis technique to analyse the results of wind resistance experiments carried out at different laboratories with models covering wide range of merchant ships. He found that the data were best fitted by the following formula:

$$F_j = 0.5\,C_j\,\rho\,V_R^2\,A_T \qquad (32)$$

Where:

F_j = fore, after and lateral components of wind force, in KN.
ρ = air density, in Kg/m^3.
V_R = relative wind speed, in knots.
A_T = transverse projected area of the ship, in m^2.
C_j = a coefficient depending on whether the wind is in the for and aft or lateral direction.

Accordingly, the wind resistance is determined as follows:

$$R_{WN} = F_j \cos \gamma \qquad (33)$$

Where:

R_{WN} = wind resistance, in KN.
γ = wind angle, in degrees.

5. Case study

A container ship whose particulars are given in Table (2) [33], is used to validate the proposed procedure, for the following reasons:

1. The container ship is a fast cargo ship.
2. The wind resistance represents an appreciable part of the added resistance in a seaway, particularly, when fully loaded.

A computer program is developed, in modular form, to calculate the following [34];

1. Still water resistance; using Holtorp's formulae.
2. Added resistance due to wind; using Isherwood formulae.
3. Resistance due to in-service hull roughness; which includes resistance due to fouling.
4. Added resistance due to waves in a seaway; using formulae developed by V. Jinkine and V. Ferdnande.

Table (2) : Main particulars of case study ship "HOLANDIA"

HULL:		
Length overall all, L_{oa}	204.0	m
Length of load waterline, L_{LWL}	196.7	m
Length between perpendiculars, L_{pp}	193.1	m
Breadth, B	30.8	m
Draught, T	10.0	m
Displacement, ∇	5709.0	m^3
Block coefficient, C_B	0.6	
Centre of buoyancy	-1.14%	L_{pp}
Longitudinal radius of gyration, K_{yy}	23.0%	L_{pp}
Watted surface area, S	6869.0	m^2
Layers of containers	2	
Lateral projected area	3725.0	m^2
Transverse projected area	725.0	m^2
ENGLINE :		
Power, MCR	29000.0	hp
RPM	122	
PROPELLER:		
Diameter, D	6.15	m
Number of blades, Z	6	
Expanded blade area ratio, A_e / A_o	0.90	
Pitch ratio, P/D	0.9626	
SHIP SPEED	20 Knots	

5.1 Discussion of results

The added resistance is calculated for the case study ship; container ship "Holandia", travelling in North Atlantic Ocean. The seaway is described by the developed family of wave spectra. Each family onsists of a significant wave height, HS, and a range of modal frequencies, ω_m. The calculated dded resistance is represented in Fig. (6) and Fig. (7).

n general, Fig. (6) shows that, the added resistance increases with the increase of significant wave eight and modal frequency. At a sea state, 7, which corresponds to a significant wave height of 7 neters, the encountered added resistance is almost the same as the still water resistance, in case of naintaining the service speed.

The effect of the wave modal period (frequency), in Fig. (7) is illustrated. It is easy to note that the added resistance increases to a peak and then falls down. The encountered added resistance reaches its maximum at the most probable modal frequency, which ranges between 0.53 and 0.63 rad/s and represents, together with significant wave height, the most probable wave spectra likely to occur.

The calculated added resistance due to sea waves and wind, is compared with those measured in full scale trials of the case study ship, Holandia[43], as shown in Table (3). The differences between measured and calculated resistance is not of great magnitude. These differences are due to the errors in measuring devices and/or the high non-linearity of sea state as shown in Table (4).

A further analysis of the calculated resistance of the case study ship is carried out. Fig. (8) shows the percentage frequency of occurrence of effective power all the year according to Table (5), while Fig. (9), shows the same in winter. These figures show that, beyond a sea state of 6 meters significant wave height, the required power to be installed, to maintain service speed, would be tremendous and unrealistic. The percentage frequency of occurrence of such sea state would be about 5%. In that rough weather, the ship has to reduce her speed to reduce the ship motions to ensure the safety of the ship. The relative importance of the added resistance components is well illustrated in Fig. (10).

The magnitude of the effective power required to counteract the adverse effect of roughness increase in service; which considered a moderate fouling growth rate, is about 12%. Therefore, the extra power needed is significantly reduced if a regime is followed to remove the fouling and improve the surface finish of the hull surface, specially in docking.

5.2 Probability density function of sea margin

The calculated added resistance and the corresponding power; sea margin, in a seaway are statistically analyzed to find out the density distribution that fits these data. The analysis revealed that the data is best fitted by the normal distribution low, as shown in Fig. (11). With the use of statistical lows the mean and variance of the density function could be easily obtained. Accordingly, the probability density function of sea margin, SM,

$$\int(\mathrm{SM}) = \frac{1}{\sqrt{2\pi}\,\sigma} \exp - \frac{1}{2}\left(\frac{\mathrm{SM} - \mu}{\sigma}\right)^2 \qquad (34)$$

Where :

μ = The mean value of sea margin for a particular ship, travelling long certain trade route.

σ = The variance of sea margin.

Having obtained the density function of sea margin, the naval architect will be able to assign, rationally, the extra power required over still water power, for a known probability of attaining service speed according to the chosen sea margin. Accordingly, the ship designer and/or ship owner will be aware of the probability that the ship will fail to maintain her service speed in advance. This could be defined as a risk factor as follows :

$$\varepsilon = 1 - F(\mathrm{SM}) \qquad (35)$$

Where :

ε = risk factor

F(SM) = cumulative normal probability distribution of sea margin.

6. Conclusion:

From the work carried out, the following conclusions have been made:

1. In the frame work of system engineering, a rational approach for evaluation of the required sea margin is successfully developed. The method is made simple so as to allow the ship designer to implement it in order to calculate how much reserve power should be available to satisfy the projected ship performance.

2. In the development of the calculation procedure of the sea margin, a series of two-parameter wave spectra is considered to include the variability of Sea State, and hence, improve the reliability of the proposed approach.

3. The available data on in-service hull roughness has shown that the best fit to the variability of the hull roughness was found to be lognormally distributed.

4. The ship economist can now, rationally, elaborate his feasibility studies for the proper selection of the ship propelling power, based on the determined probability density function.

5. The results of this work are limited to the cases of prime mover(s) having deterministic characteristics.

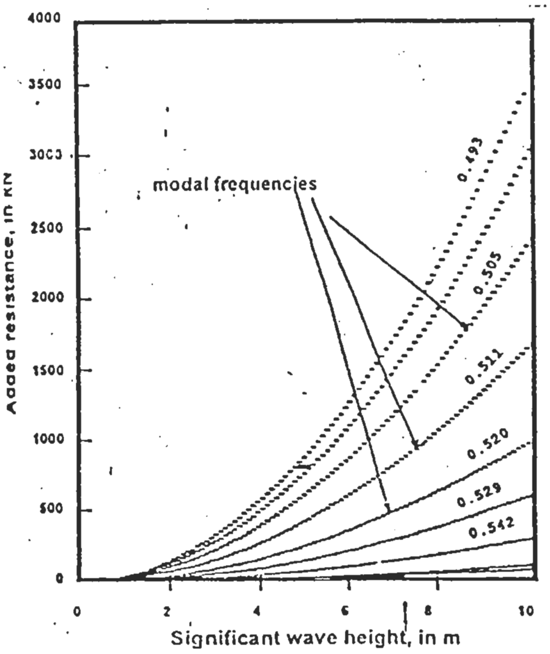
6. The proposed procedure is developed for fast cargo ship. However, this approach is presented in modular form so as to accommodate easily other types of ships.

Table (3) Measured and calculated resistance for case study ship "HOLANDIA"

1980	SPEED		RESISTANCE			ADDED RESISTANCE	
Run No.	Ship V knots	Engine N rpm	Seaway Measured (R_{T}.) KN	S. Water Calculated (R_{sw}) KN	Seaway calculated (R_T) proposed approach KN	$\left(\frac{R_T - R_{SW}}{R_{SW}}\right)$ Measured	$\left(\frac{R_T - R_{SW}}{R_{SW}}\right)$ % Calculated proposed approach
51	15.39	113.74	1318.46	581.73	1288.14	127	121.0
58	12.54	91.65	857.40	441.04	831.67	109	88.6
59	6.81	58.05	407.12	130.48	387.98	212	197.0
64	17.22	116.76	1286.09	696.51	1243.39	85	78.5

Table (4) Weather conditions during full scale trials of case study ship "HOLANDIA"

1980	DATE & TIME		WIND		SEA WAVES	
Run No.	DATE	TIME	V_w Knots	$O_{w,}$ off bow degrees	Significant wave height m	Wave period Sec.
51	5-1-80	10.01	21.7	003 PS	6.7	12.0
58	6-1-80	16.45	25.1	015 SB	4.6	09.9
59	6-1-80	17.20	25.7	023 SB	5.1	10.3
64	6-1-80	22.25	21.9	036 SB	5.2	10.7



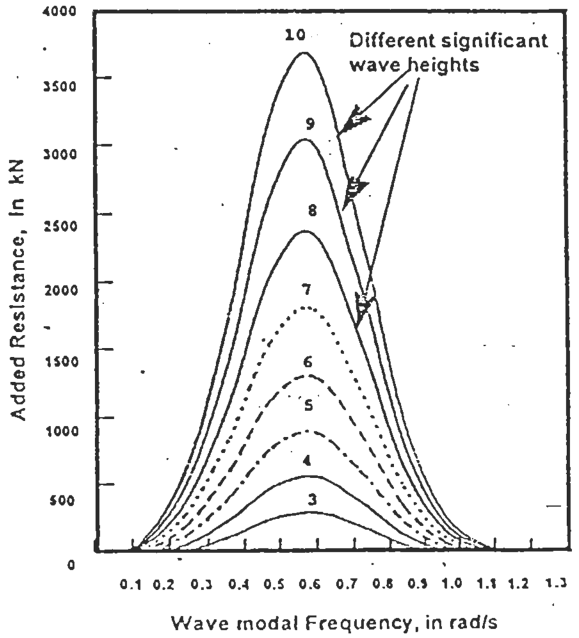


Table (5) Sea state occurrences in North Atlantic

Significant Wave Height, m	Percentage Probability of Sea State		
	All Seasons	Winter	Summer
< 0.5	7.20	4.60	7.50
0.5 – 1.25	22.40	7.50	12.50
1.25 – 2.5	28.70	38.50	52.90
2.5 – 4.0	15.50	25.40	19.80
4.0 – 6.0	18.70	15.30	5.30
6.0 – 9.0	6.10	5.40	0.90
9.0 – 14.0	1.20	2.80	0.10
> 14	0.05	0.20	0.00

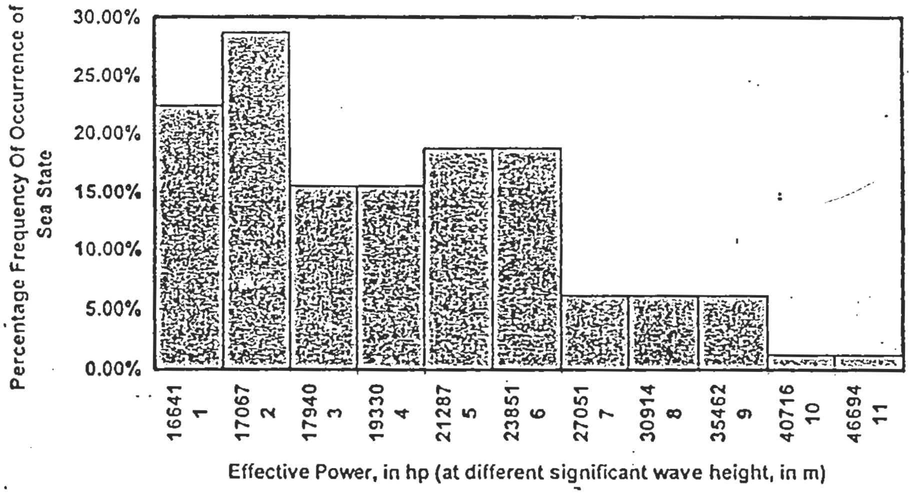


Fig. (8): Percentage frequency of occurrence of effective power for case study ship "HOLANDIA" in North Atlantic all seasons

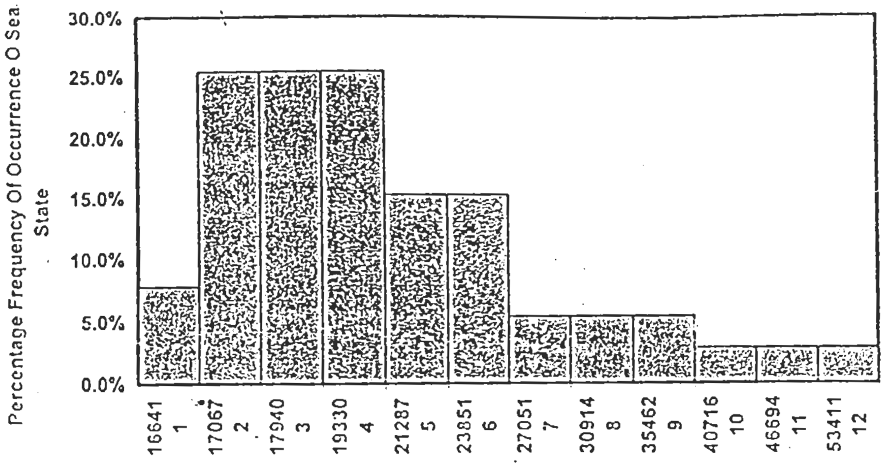


Fig. (9): Percentage frequency of occurrence of effective power for case study ship "HOLANDIA" in North Atlantic Winter

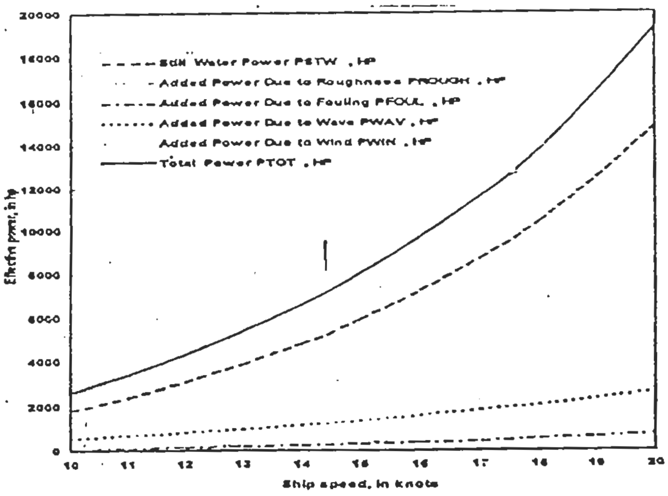


Fig. (10): Effective power of a sea state of significant wave height 4 meters in North Atlantic

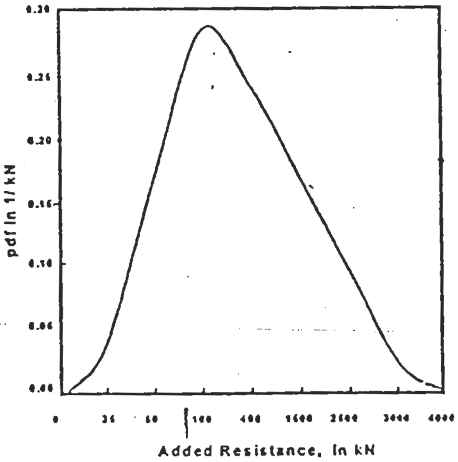


Fig. (11): Probability density function of added resistance for case study ship "HOLANDIA"

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Appendix :

In-Service Hull Roughness

The average roughness of shotblasted and primed stock plate in shipyards was found in the rage of 40 to 60 μm, and the nominal dry film thickness of a typical paint system on ship's hull is in the range of 300 to 600 μm. It is clear that the cause of this roughness is due to the nature of the applied paint together with any inadequacies in the application process [33].

New ships entering service :

The roughness of the ships beginning service was measured and a data were produced by BSRA, for ships built between 1966 and 1975 in which the mean value was 142 μm and the modal value 125 μm. R.L. Townsin et al [33] performed another survey on a total of 47 newly built ships beginning service. The hull roughness was found distributed about a mean value of 129 μm with a modal value of 125 μm, which is comparable to the results obtained by BSRA. Fig. (18) shows typical components of new ship hull roughness.

Increase of Hull Roughness due Ship's Operation.

In fact, the hull roughness increases with age of ship, however, there is no simple relationship between roughness and age, as is clear from the scatter of the data points in Fig.(14)[45]. This wide scatter occurs because the contributors to the hull roughness vary randomly with time. Decomposing the hull roughness into its main components may lead to a better understanding of the phenomena, and hence, we can deduce, to some extent, a rational relationship between hull roughening in service and the ship's age.

Analysing the data shown in Fig. (16), for a three-years old ship, revealed that the changes in hull roughness can be decomposed into :

1. Changes in hull roughness during in-service time is found to be due to corrosion of steel substrate which depends on the effectiveness of the anti-corrosion coating and the catholic protection. Some of the roughness due to corrosion becomes a permanent hull surface characteristic. Also, mechanical damage is found to be a major contributor to the in-service hull roughness.
2. Changes in hull roughness during dry docking, in general, more than 68% of the hulls increase in roughness during dry docking. Such increase is 25 μm on the average, and only 16% became less rough [45].

Increase in hull roughness due to fouling :

The roughness due to hull fouling is influenced by three main parameters; anti-fouling coating effective life, ship's time in port and port fouling severity. It is assumed that, no fouling occurs while the ship is underway (over 3 knots). However, limited evidence has been noted that some fouling does occur underway for large slow-speed tankers [37].

The resistance due fouling was estimated by Malone et al [38]. Considering the fact that the fouling growth rate on ship's sides is slower than that on ship's bottom, a factor was applied to bottom fouling rate because fouling does not grow as fast on bottom as it does on sides. The following equation is developed based on work reported by Miro Kresic et al [37]. To predict an equivalent MAA_{FOL} :

$$MAA_{FOL} = (HRF)\,(PT)\,(CEFF)\left(\frac{(1 - FGRC)\,(LPMB)\,(B)}{WS}\right) \qquad (36)$$

Where :

HRF = hull roughness factor, in mm per port day.

PT = port time, in days.

CEFF = anti-fouling coating effectiveness factor.

= $1 - [2.72/e^{z} - 0.24\,(Z-1)^{0.263}]$

Z = ratio of accumulated time, since application of anti-fouling paint was made to effective life of anti-fouling paint.

FGRC = fouling growth rate coefficient.

LPMB = length of parallel middle body of a ship in m.

WS = wetted surface area of a ship in m.

B = breadth of a ship in m.

Equation (36) reflects, to some extent, the effect of the operation pattern on the propulsion system, since any increase in port time is translated into an in crease in ship resistance. Also, the effect of variations in ship's loading is reflected through the length of the underwater part of the parallel middle body and the wetted surface area.

Total Mean Apparent Amplitude

The total mean apparent amplitude (MAA), used to estimate the resistance due to hull roughness, is given as follows [38]:

$$MAA = MAA_{NEW} + MAA_{FOL} + MAA_{HRS}$$

Where :

MAA = Total hull roughness, in μm.

MAA_{NEW} = new building roughness, in μm.

MAA_{FOL} = fouling roughens, in μm.

MAA_{HRS} = in-service hull roughness, in μm.

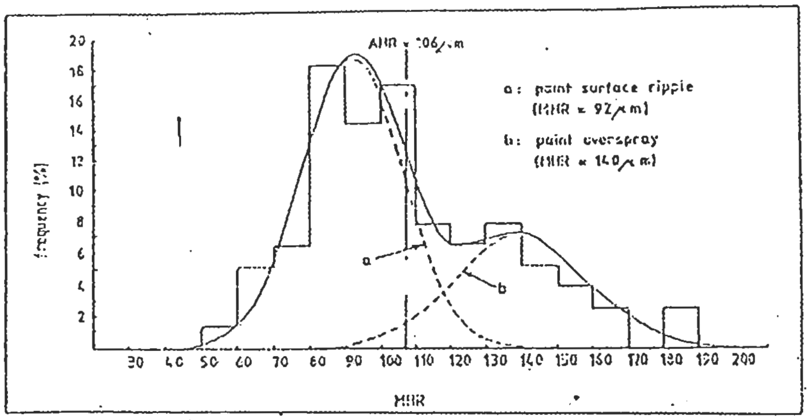

Fig. (14): Typical components of new ship hull roughness

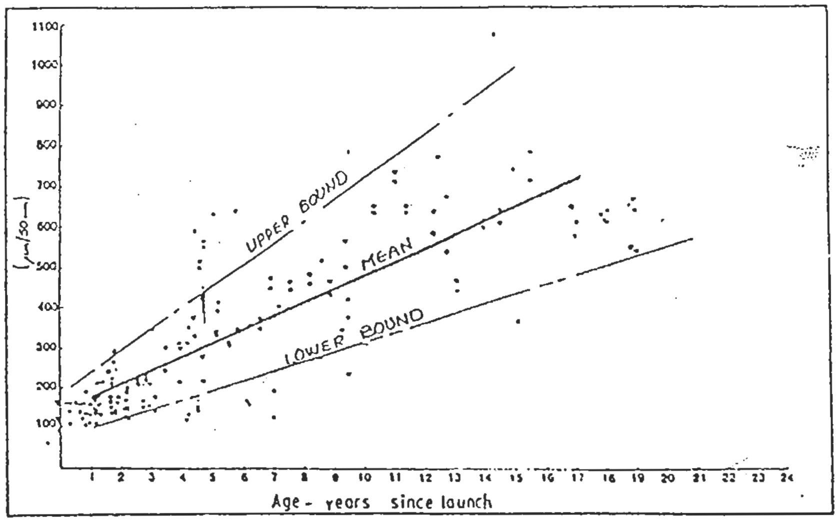

Fig. (15): Roughness of hull of various ages

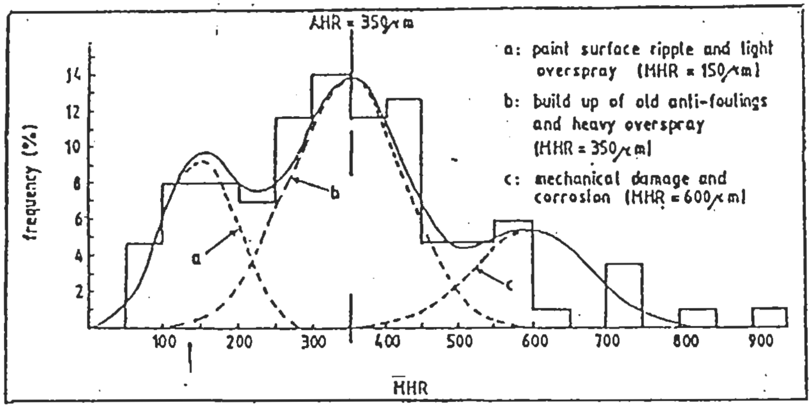

Fig. (16): Typical components of hull roughness on a ship in service