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Design of Bulbous Bows

Alfred M. Kracht,[1] Visitor

There is no doubt that bulbous bows improve most of the properties of ships, but the correct design and power prediction for ships with bulbous bows are still difficult due to the lack of design data. In the paper, a quantitative design method is presented together with the necessary data providing relationships between performance and main parameters of ships and bulbs. The data, in the form of design charts, are derived from a statistical analysis of routine test results of the Hamburg and the Berlin Model Basins, HSVA and VWS, respectively, supplemented by results of additional tests to fill the gaps. Three main hull parameters are taken into account: block coefficient, length/beam ratio, and beam/draft ratio, while six bulb quantities are selected and reduced to bulb parameters, of which the volume, the section area at the fore perpendicular, and the protruding length of the bulb are the most important. For power evaluation, the total power is subdivided into a frictional and a residual part. Depending on bulb parameters and Froude number for each block coefficient of the main hull, six graphs of residual power reduction have been prepared. Because of the wide range of block coefficients, there are so many design charts that only one example is presented herein.

Introduction

NEARLY 90 YEARS AGO, R. E. Froude [1][2] interpreted the lower resistance of a torpedo boat, after fitting of a torpedo tube, as the wave reduction effect of the thickening of the bow due to the torpedo tube. D. W. Taylor was the first who recognized the bulbous bow as an elementary device to reduce the wavemaking resistance. In 1907 he fitted the battleship *Delaware* with a bulbous bow to increase the speed at constant power. In spite of great activities in the experimental field to explore its potential, 70 years had to pass before the bulb finally asserted itself as an elementary device in practical shipbuilding. A suitably rated and shaped bulb affects nearly all of the properties of a ship. Especially for fast ships, the use of a bulb allows a departure from hitherto accepted design principles for the benefit of a better underwater form. The higher building costs are the only disadvantage.

The protruding bulb form affects hydrodynamically a variation of the velocity field in the vicinity of the bow, that is, in the region of the rising ship waves. Primarily the bulb attenuates the bow wave system, which usually is accompanied by a reduction of wave resistance. By smoothing the flow around the forebody, there is good reason to believe that the bulb tends to reduce the viscous resistance too. Therefore, the beneficial action of a protruding bulb depends on the size, the position, and the form of the bulb body. See Fig. 1.

The linearized theory of wave resistance has provided the main contribution to the understanding of the bulb action (Wigley [3], Weinblum [4], Inui [5, 6]). But it is of no great use for the project engineer. In the preliminary stage of his project, he needs fundamental information on which to base concrete decisions. Later, in the realization stage, the quantitative as well as qualitative guidelines are important, because the hydrodynamic phenomena are not describable by few geometric form parameters alone. For this reason, in this paper, the mode of action of a bulb and the influence of bulb parameters on resistance or power reduction, respectively, are described in a qualitative manner; guidelines for bulb design are also introduced. The design charts presented here are the result of a research project; that is, of an analysis of routine test results, of the Hamburg and the Berlin Model Basins supplemented by results of additional tests to fill the gaps. The charts are new and therefore still in need of improvement and completion.

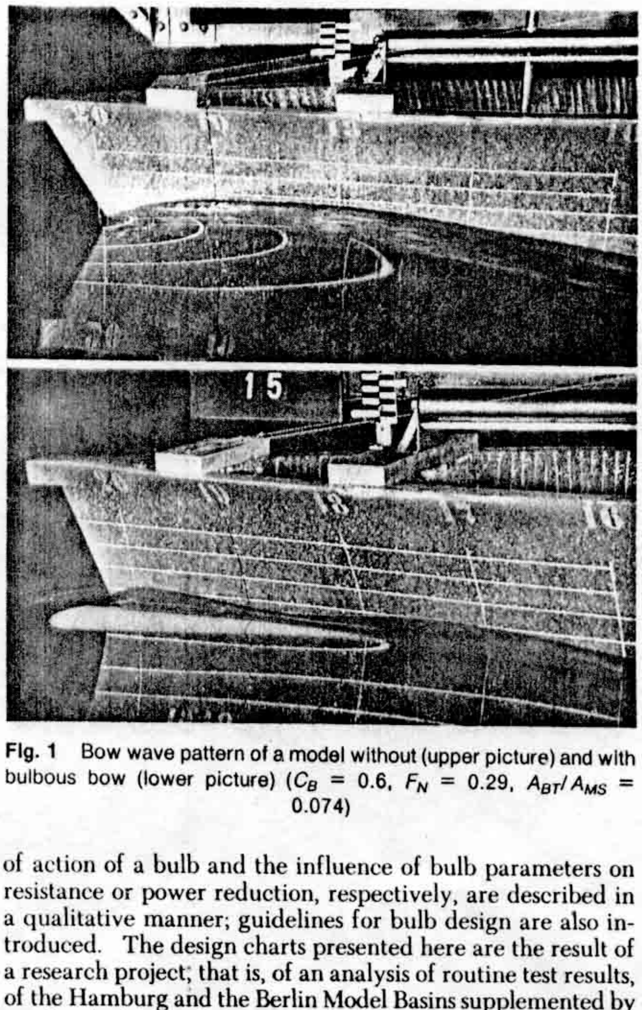

Fig. 1 Bow wave pattern of a model without (upper picture) and with bulbous bow (lower picture) (C_B = 0.6, F_N = 0.29, A_{BT}/A_{MS} = 0.074)

[1] VWS Berlin Model Basin, Berlin, Germany.

[2] Numbers in brackets designate References at end of paper.

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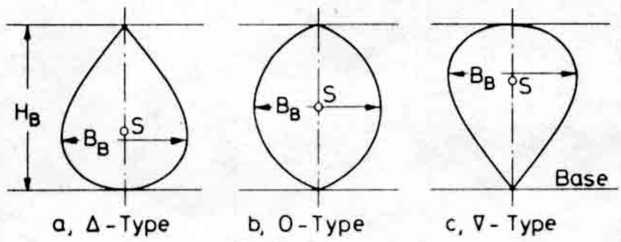

Fig. 2 Bulb types

free surface. Because of its favorable seakeeping properties, this type is the most common bulb.

With respect to the lateral contour of the bulbous bow, two typical classes are distinguishable:

(*a*) The stem outline remains unchanged as with the Taylor bulb. These bulbous bows do not have favorable properties and are no longer built today.

(*b*) The stem outline is changed by the protruding bulb as with all modern bulbous bows.

In addition to these classification criteria, quantitative bulb parameters are necessary for delineation of the bulb form. The author is of the opinion that six parameters are sufficient for all practical purposes. Figure 3 shows the three linear and three nonlinear geometric bulb quantities that are reduced to the bulb parameters, that is, normalized by the main dimensions of the ship, as described in the following.

The three linear bulb parameters are

1. The breadth parameter, that is, the maximum breadth B_B of bulb area A_{BT} at the *FP* divided by the beam B_{MS} of the ship

$$C_{BB} = B_B/B_{MS} \qquad (1)$$

2. The length parameter, that is, the protruding length L_{PR} normalized by the L_{PP} of the ship

$$C_{LPR} = L_{PR}/L_{PP} \qquad (2)$$

3. The depth parameter, that is, the height Z_B of the foremost point of the bulb over the base divided by the draft T_{FP} at the *FP*

$$C_{ZB} = Z_B/T_{FP} \qquad (3)$$

The variation of the linear bulb parameters is easily possible during the project phase. The breadth B_B is not necessarily the maximum breadth of the bulb body that, for hydrodynamic reasons, can also be located before the *FP*. The depth pa-

Bulb forms and parameters

For an adequate presentation of the hydrodynamic properties of bulbs, it is necessary to systematize the different existing bulb forms [7] by means of geometric parameters. Obviously a definitive description of a bulb shape, just as for a ship form, with a finite number of geometric parameters, is impossible. But a rough classification is possible using only few parameters.

With the shape of the cross section A_{BT} of the bulbous bow at the forward perpendicular (*FP*) as the main criterion, one can differentiate three main bulb types (Fig. 2) [8]:

(*a*) Δ-Type: Fig. 2(*a*) shows the drop-shaped sectional area A_{BT} of the delta-type with the center of area in the lower-half part. This shape indicates a concentration of the bulb volume near the base. The Taylor bulb and the pear-shaped bulbs belong to this type.

(*b*) O-Type: This type (Fig. 2*b*), with an oval sectional area A_{BT} and a center of area in the middle, has a central volumetric concentration. All the circular, elliptical, and lens-shaped bulbs as well as the cylindrical bulbs belong to this type.

(*c*) ∇-Type: The nabla-type also has a drop-shaped sectional area A_{BT} (Fig. 2*c*), but its center of area is situated in the upper-half part, indicating a volume concentration near the

Nomenclature

A_{BL} = area of ram bow in longitudinal plane, m²
A_{BT} = cross-sectional area at forward perpendicular (FP), m²
A_{MS} = midship section area, m²
B_B = maximum breadth of bulb area A_{BT}, m
B_{MS} = beam, midship, m
C_B, C_M, C_P, C_{WL} = block, midship-section, prismatic, and waterline coefficients, respectively
C_{PE} = prismatic coefficient, entrance
C_F, C_R = frictional or residual resistance coefficient, respectively
$C_{P\nabla R}$ = residual power displacement coefficient
$\Delta C_{P\nabla R}$ = residual power reduction coefficient
C_{ABL} = lateral parameter
C_{ABT} = cross-section parameter
C_{BB} = breadth parameter
C_{LPR} = length parameter
$C_{\forall PR}$ = volumetric parameter
C_{ZB} = depth parameter
D, D_{wake} = diameter of propeller, or wake field, respectively, m
$F_N = V_S/\sqrt{g \times L_{PP}}$ = Froude number
H_B = total height of A_{BT}, m
L_E, L_{PP} = length of entrance, or between perpendiculars, respectively, m
L_{PR} = protruding length of bulb, m
P_D, P_F, P_R = delivered, frictional, or residual power, respectively, PS
P_{EF}, P_{ER} = effective frictional or effective residual power, respectively, PS
ΔP_R^* = residual power reduction factor
R_F, R_T, R_V = frictional, total, or viscous resistance, respectively, kp
R_{VR}, R_{WB}, R_{WF} = viscous residual, wave-breaking, or wavemaking resistance, respectively, kp
$\Delta R_{WB}, \Delta R_{WF}$ = bulb effect on wave-breaking or wavemaking resistance, respectively, kp
ΔR_V = secondary bulb effect, bulb effect on viscous resistance, kp
$R_N = V_S \times L_{PP}/\nu$ = Reynolds number
S, S_{Btot} = ship surface or total bulb surface, respectively, m²
T_{FP}, T_{MS} = draft at *FP* or midship, respectively, m
V_S = ship speed, knots
$\forall_{Btot}$ = total bulb volume, m³
$\forall_{PR}$ = volume of protruding bulb part, m³
$\forall_{WL}$ = displacement volume, m³
Z_B = height of the foremost bulb point over baseline, m
t, w = thrust deduction or wake fraction, respectively
η_D = propulsive efficiency
ν = viscosity of water, s/m²
ρ = density of water, kp·s²/m⁴
g = acceleration due to gravity, m/s²

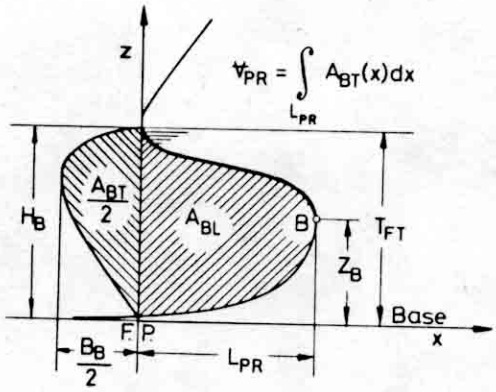

Fig. 3 Linear and nonlinear bulb quantities

rameter is a valuation factor of the beach slope of the bulb top (thick line in Fig. 3).

The three nonlinear bulb parameters are

1. The cross-section parameter, that is, the cross-sectional area A_{BT} of the bulbous bow at the FP divided by the midship-section area A_{MS} of the ship

$$C_{ABT} = A_{BT}/A_{MS} \tag{4}$$

2. The lateral parameter, that is, the area of ram bow A_{BL} in the longitudinal plane normalized by A_{MS}

$$C_{ABL} = A_{BL}/A_{MS} \tag{5}$$

3. The volumetric parameter, that is, the volume $\forall_{PR}$ of the protruding part of the bulb divided by the volume of displacement $\forall_{WL}$ of the ship

$$C_{\forall PR} = \forall_{PR}/\forall_{WL} \tag{6}$$

The volume $\forall_{PR}$ is the nominal bulb volume. The total or effective bulb volume $\forall_{Btot}$ is the sum of $\forall_{PR}$ and the fairing volume $\forall_F$, which results from the fairing of the bulb into the ship hull.

Finally, a distinction is possible between an additive and an implicit bulb. An additive bulb increases the displacement volume $\forall_{WL}$ of the ship by the effective bulb volume $\forall_{Btot}$. The sectional area curve of the original hull remains unchanged. On the other hand, the effective volume $\forall_{Btot}$ of an implicit bulb is part of the displacement volume $\forall_{WL}$ of the main hull that is shifted from unfavorable regions and concentrated in the vicinity of the forward perpendicular. By this process, the sectional area curve of the original ship is changed.

Influence of a bulbous bow on the properties of a ship

Before discussing the influence of the bulbous bow on the ship's resistance and required power, respectively, we should mention other important hydrodynamic qualities which play a role in the decision whether a bulb should be used or not. The change of resistance influences the thrust loading of the propeller and, consequently, other propulsive characteristics of the ship; for example, the quasi-propulsive coefficient, the wake, and the thrust deduction fraction [9–11]. Figure 4 shows this indirect influence of a bulbous bow on thrust deduction and wake fraction. Both are increased by an additive as well as by an implicit bulb, if the bulb ship has a lower total resistance than the bulbless form. But there is also a direct influence of the bulbous bow on the wake distribution in the propeller plane. In Fig. 5 the radial distributions of axial wake components of ships with and without a bulb are compared. Within the propeller disk area the axial wakes of all bulb ships are higher than the wakes of the bulbless ones. The reason for this is the change of flow around forebody and bilge, which is observable in the model case up to the propeller disk [12, 13]. But in the correlation of model test and full-scale results, scale effects play a very important role [10] and it is not certain if this bulb effect is also found at the ship.

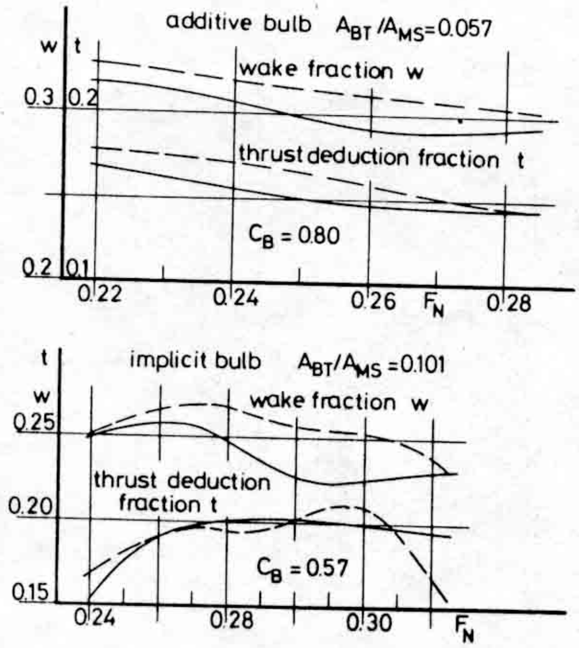

Fig. 4 Influence of a bulbous bow on thrust deduction and wake fraction (- - - - - with, —— without bulb)

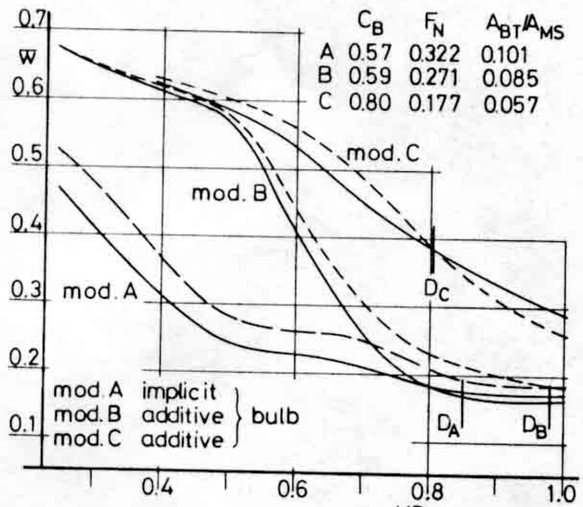

Fig. 5 Influence of a bulbous bow on the radial distribution of circumferencial average nominal axial wake component (- - - - - - - with, —— without bulb)

Although unfavorable effects are possible, bulbous bows in general do not influence the course stability or the maneuverability [14]. No significant changes of the overshoot angle or the period in zigzag tests could be established. The bulb is an ideal place for the arrangement of bow thrusters and acoustic sounding gears.

The seakeeping qualities of a ship are a special problem, and a very broad field, which will be discussed here only briefly.

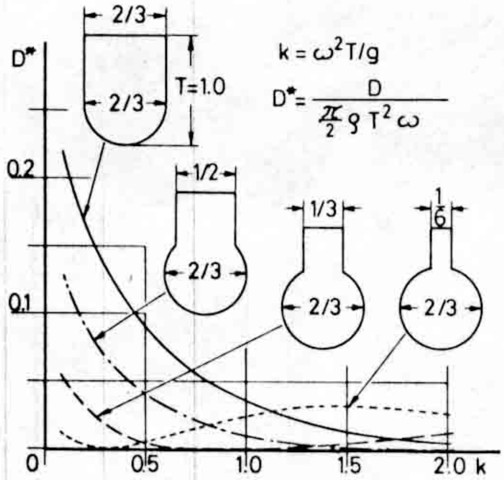

Fig. 6 Damping coefficient D^* of partially immersed bulbous cylinders as function of wave number k [18]

Except for the relative foreship motion against the water surface, the bulbous bow has no unfavorable influence on either the remaining motions or on the maximum bending moment in the midship section [15, 16]. In spite of the higher relative motion of a bulb ship, the danger of slamming of a well-shaped bulb is no higher than with the bulbless ship [17]. In detail, the bulb mitigates the pitching motion of the ship by its higher damping. It should be mentioned here that the damping coefficient of bulb cylinders in a two-dimensional case vanishes for a certain wave number [18] as shown in Fig. 6. Since nonbulbous cylinders do not show this quality, the damping effect of a bulbous bow, for example, of O-type, can vanish for definite wave numbers, and the bulb ship moves like a bulbless one.

In regular waves, model tests show that the critical Froude number F_N from which the bulb ship begins to be superior increases with increasing ratio λ/L [15]. As a function of λ/L at constant Froude number, the resistance of a bulb ship increases more rapidly than that of the bulbless form. Therefore, most of the smooth-water advantages of bulb ships vanish above about $\lambda/L = 0.9$. In irregular waves, nearly all bulbous ships have disadvantages above Beaufort 8. Since in the North Atlantic the probability of the occurrence of wind intensity more than Beaufort 8 is only about 10 percent, and up to $\lambda/L = 0.8$ the bulbous ship is the best ship [20] regardless of seakeeping aspects, the bulb design consequently may be carried out in view of the smooth-water performances only.

In navigation in ice, the bulbous bow has proved to be advantageous. Its form enables a tipping of ice floes coming from the front in such a way that they glide along the hull of the foreship with their wet-side friction coefficient, which is small. Due to this effect, the speed loss of a ship with a bulbous bow is smaller than that of a bulbless one.

If from the beginning a bulbous bow is included in the shaping of the underwater hull form, then for fast ships especially it is possible to leave the traditional recommendations on the fullness of the forebody and the unavoidable abaft position of the center of buoyancy. Without disadvantages, the bow bulb allows a fuller foreship form and therefore better trim and stability properties. Using an implicit bulb, a more slender aft-body is possible at constant total block coefficient with improved propulsive performance. Without increase of the resistance, a greater angle of entrance for the waterlines can be used as compared with the accepted practice so far [22].

Resistance and bulb effect

The most important effect of a bulbous bow is its influence on the different resistance components and consequently on the required power. Although the design charts represent the power reduction due to a bulb, for a better understanding the hydrodynamic phenomenon shall be discussed by means of the influence of the bulb on the resistance. For this purpose, the following subdivision of the total resistance is used

$$R_T = R_V + R_{WF} + R_{WB} = R_F + R_{VR} + R_{WF} + R_{WB} \quad (7)$$

where

R_V = viscous resistance
R_F = frictional resistance
R_{VR} = viscous residual resistance
R_{WF} = wavemaking resistance
R_{WB} = wave-breaking resistance

The latter two components are related to wavemaking. Their contributions to the total resistance are very different for ships with different block coefficients and speeds. Here, an explanation is to be found for the fact that the resistance reduction due to a bulb for full, slow ships can exceed the wave resistance alone, which at $F_N < 0.2$ is a negligible part of the total resistance.

The additional bulb surface always increases the frictional resistance R_F, which is the main part of the viscous component R_V. Up to now, it is not quite clear whether the bulb affects the viscous residual resistance R_{VR} due to the variation of the velocity field in the near bow range [25, 26]. But in the reanalysis of test data based on Froude's method, presented here, this open point is of no account.

There is no doubt concerning the influence of the bulbous bow on wavemaking resistance R_{WF}. The linearized theory of wave resistance has rendered the most important contribution to the clarification of this problem [3, 4]. According to this theory, the bulb problem is a pure interference problem of the free wave systems of the ship and the bulb. Depending on phase difference and amplitudes, a total mutual cancellation of both interfering wave systems may occur. The position of the bulb body causes the phase difference, while its volume is related to the amplitude. The wave resistance is evaluated by analysis of the free wave patterns measured in model experiments [5, 26–28].

The wave-breaking resistance R_{WB} depends directly on the rising and development of free as well as local waves in the vicinity of forebody and is a question of typical spray phenomenon. Understanding of the breaking phenomenon of ship waves is important for the bulb design for full ships. R_{WB} includes all parts of the energy loss by the breaking of too-steep bow waves. The main part of this energy can be detected by wake measurements [23, 26]. The local wave system contributes the main part to this resistance component. This wave system consists mainly of the two back waves of bow and stern which are generated by deflection of the momentum. The deflection rate of the flow is a degree of the steepness of these back waves, of which only the bow wave is of a practical importance in bulb design.

The wave-breaking resistance can be diminished only insofar as it is possible to prevent the breaking of bow waves. According to the reason of its creation, this is only possible by changing the deflection of momentum or the bow near the velocity field, respectively. In principle this may be achieved not only by a bulbous bow, but by suitable hydrofoils as well [29]. A theoretical treatment of the linearized problem has recently begun [23, 30].

The effect of the bulb on the different resistance components can be discerned by taking the differences of the corresponding resistance components of the ship without (index o) and with bulb (index w):

$$\Delta R_T = R_{To} - R_{Tw} = \Delta R_V + \Delta R_{WF} + \Delta R_{WB} \qquad (8)$$

Consequently it is possible to define three different bulb effects. In any case, a positive bulb effect ΔR means a resistance reduction, and vice versa. The two latter terms in equation (8) account for the primary bulb effect, which for bulb design are the most important. The difference of the wave resistances

$$\Delta R_{WF} = R_{WFo} - R_{WFw} = R_{WI} + R_{Wb} \qquad (9)$$

is the interference effect, which is the sum of the interference resistance R_{WI} and the wave resistance of the bulb body R_{Wb} alone. Its contribution to the total bulb effect can be estimated by an analysis of the interfering free wave patterns [26]. According to Froude's law, it can be scaled directly to the full-scale ship. Only for slender fast ships does it give the main proportion to the total bulb effect, where the amount depends essentially on the bulb volume and the sign on the longitudinal position of the bulb center.

The difference between the wave-breaking resistances

$$\Delta R_{WB} = R_{WBo} - R_{WBw} \qquad (10)$$

is the breaking effect, which is the main contribution to the total bulb effect for full, slow ships. Its contribution is: the bigger the bulb, the better the deflection of the flow in the vicinity of the bow region. This means for the bulb form an optimal distributed bulb volume in the longitudinal direction to minimize gradients of the hull surface in the region of rising bow waves. Using geosim model tests, Taniguchi [12] and Baba [23] have shown that the wave-breaking resistance, and consequently the breaking effect, is Froude number dependent.

The difference between the viscous resistance parts

$$\Delta R_V = R_{Vo} - R_{Vw} = (R_{Fo} - R_{Fw}) + (R_{VRo} - R_{VRw}) \qquad (11)$$

is the secondary bulb effect, which is of minor importance for the total bulb effect. Due to the larger surface of bulb ships, the frictional resistance term of equation (11) is always negative and diminishes the bulb action. For reasons mentioned before, the contribution of the difference of viscous residual resistance is not taken into account.

Finally, the question has to be answered whether equivalent variations of the ship may result in the same improvements as an addition of a bulb, for example, an increase of block coefficient C_B corresponding to the bulb volume, or an elongation of the ship length corresponding to the bulb length L_{PR}. It has been shown by model experiments [14] and by linear theory [22] that the effect of a bulb cannot be achieved by form variations [9].

Influence of bulb parameters on bulb effect

At constant Froude number F_N, the bulb effect is a function of all six bulb parameters:

$$\Delta R = F(C_{\nabla PR}, C_{ABT}, C_{ABL}, C_{LPR}, C_{BB}, C_{ZB}) \qquad (12)$$

This multidimensional relationship complicates the understanding of the dependencies on single parameters, the knowledge of which is very helpful for bulb design. Unfortunately, a quantitative description of these dependencies is possible in only a few cases, because systematic model experiments are too expensive and some parameters cannot be varied independently. On the basis of linearized wave resistance theory, however, a qualitative picture can be developed, supported by special model experiments, for example, the wave cuts [26], which not only prove the tendency of the dependence.

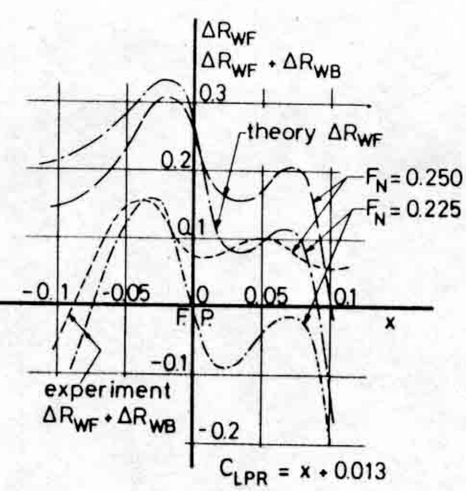

Fig. 7 Dependence of interference and primary bulb effect on the length parameter $C_{LPR} = L_{PR}/L_{PP}$. Comparison of theory and experiment with an elementary ship of the form (2,4,6,0.72,1.0) [31]

Because of the doubts connected with the secondary bulb effect, the following consideration is confined to both parts of the primary effect only—to the interference and breaking effects, respectively. The relationship between the two and the magnitude of their contributions to the total bulb effect are not discussed at this stage.

According to linearized theory, the interference effect depends on the volumetric parameter $C_{\nabla PR} = \nabla_{PR}/\nabla_{WL}$ in a quadratic manner [32]. $C_{\nabla PR}$ is a measure of the amplitude of the wave pattern. The breaking effect shows a similar dependence. With increasing bulb volume, both effects increase up to a maximum with a subsequent decrease. The optimal bulb volumes corresponding to the maximum values of the different bulb effects do not, in general, coincide. For the interference effect, the optimal volume can be estimated for a given ship-bulb combination by the wave cut method [26]. In a similar way, the interference effect depends on the breadth and cross-section parameter.

For a constant bulb volume and depth, the length parameter $C_{LPR} = L_{PR}/L_{PP}$ has a great influence on the interference effect. As it is a measure for the phase relation of the free wave systems of ship and bulb, typical maxima and minima appear as a direct consequence of the interfering waves. As shown in Fig. 7, this tendency is confirmed by model experiments [31]. The influence of the length parameter on the breaking effect can be caught intuitively by its mode of action. With increasing C_{LPR}, this effect increases at first and after a maximum decreases monotonically to zero, due to the fact that the deflection of momentum in the vicinity of the bow is hardly altered by a very long cylindrical bulb. Because the lateral parameter is strongly related to the length parameter, its influence on the bulb effect is similar.

The dependence of the interference effect on the depth parameter $C_{ZB} = Z_B/T_{FP}$ is described simply by linear theory because the term Z_B of a spherical bulb coincides with the center of the sphere. If such a bulb of constant volume and longitudinal position is moved from infinite depth up to the water surface, the interferential effect increases at first monotonically from zero to a maximum, decreases subsequently, and finally becomes negative due to an increase of the resistance of the emerging bulb body. The breaking effect behaves similarly, but it can become positive again, if $Z_B > T_{FP}$, as with the ∇-type. In this case the behavior of a ship-bulb combination is similar to a longer main hull increased in length by L_{PR}.

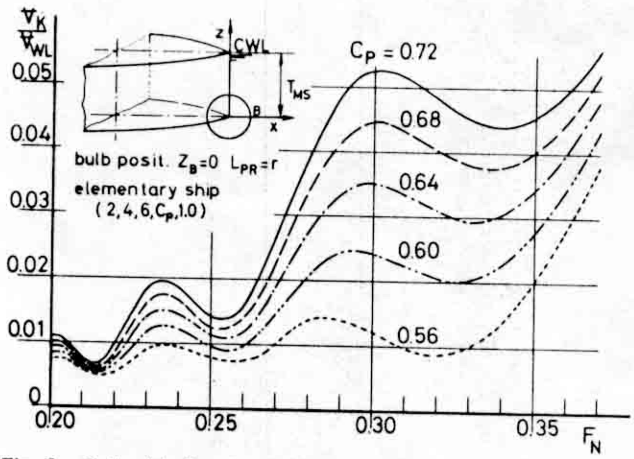

Fig. 8 Optimal bulb volume $\forall_k$ of a ship-bulb combination as a function of Froude number F_N. The prismatic coefficient C_P of the elementary ship form $(2,4,6,C_P,1.0)$ is the parameter of the curves [31]

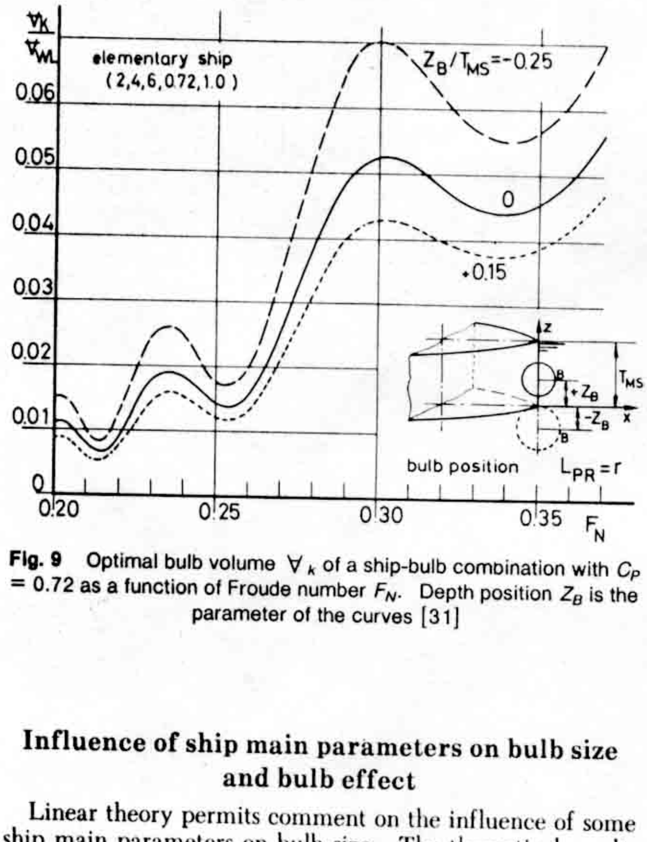

Fig. 9 Optimal bulb volume $\forall_k$ of a ship-bulb combination with $C_P = 0.72$ as a function of Froude number F_N. Depth position Z_B is the parameter of the curves [31]

Influence of ship main parameters on bulb size and bulb effect

Linear theory permits comment on the influence of some ship main parameters on bulb size. The theoretical results relate to the interference effect only, but have general validity throughout and, in particular, are applicable to the breaking effect. For discussion, the most suitable case is the optimal bulb, which minimizes the wave resistance of a ship-bulb combination. With elementary ships of the form $(2,4,6,C_P,1.0)$ [31], it may be shown that an increased prismatic coefficient C_P or block coefficient C_B, respectively, is associated with increasing volume of the optimal spherical bulb. Figure 8 gives an impression of this fact. From this it follows, for ships with long parallel middlebody, that with increasing C_{PE}, L_{PM}/L_{PP} and decreasing L_E/B_{MS}, the optimal bulb volume increases (Yim [22], Fig. 4). The depth of the bulb has a similar influence. As shown in Fig. 9, at constant Froude number F_N and longitudinal position, the optimal bulb volume increases with increasing depth position Z_B. Moreover, both figures clearly indicate the enormous influence of ship speed on optimal bulb volume, which increases in an undulating manner with increasing speed. These theoretical results are upper limits for the actual effects. While their absolute values are hardly of practical interest, the tendency of the dependence of bulb volume on speed, block coefficient, length of entrance, and bulb position is useful for the actual design.

Since the wave system is created only by the nonparallel part of the main hull, and in the real fluid the forebody makes the main contribution, the length L_{PM} of the parallel middlebody has hardly any influence on the bulb size and, therefore, the same holds for the length/beam ratio L_{PP}/B_{MS} too. For ships with $L_{PP}/B_{MS} > 5.0$, the wavemaking resistance is only a function of L_E/B_{MS}, as shown by the upper limit curves in Fig. 10 (see also Baba [23], Fig. 10). The beam/draft ratio B_{MS}/T_{MS} has a great influence on bulb effect, bulb size, and draft parameter C_{ZB} (upper limit curves in Fig. 11). Consequently, for dimensioning of a bulbous bow, the main-hull parameters are C_{PE}, B_{MS}/T_{MS}, and L_E/B_{MS}. Unfortunately, in the preliminary design phase, C_{PE}, and often L_E too, is unknown. Therefore, the following design guidelines are mainly based only on block coefficient C_B and beam/draft ratio B_{MS}/T_{MS}.

Design guidelines for bulbous bows

It is well known that the existing design methods, for example, the classical method by Taylor, are not sufficient for power estimation of a bulb ship and for modern bulb design. To fill this gap in the design guidelines, a large number of routine test results of ships without and with bulb, carried out by the two German model basins, have been reanalyzed in a research project. The design guidelines derived, the design charts, and a computer program have been successfully applied on various occasions. From the multitude of diagrams developed in this paper, only one example is depicted. For complete information, reference has to be made to FDS Bericht No. 36/1973[8] and VWS Bericht No. 811/78[38]. It is emphasized that the information content of the design diagrams cannot be better than that of the original data base, especially in the cases with very small data collection.

Reanalysis of routine test results

Since the bulbous bow affects primarily the wavemaking resistance, the design guidelines should correctly be related to the wave or residual resistance. During preparation of the research work, it became evident, however, that most of the usable data were propulsion rather than resistance test results. Since in principle it makes no difference whether the bulb effect is derived from resistance or propulsion tests, a power specific bulb effect, or power reduction factor, respectively, was defined:

$$\Delta P^* = 1.0 - P_w/P_o \tag{13}$$

In this form the bulb effect is the power difference of the ship without P_o and with bulb P_w related to the power of the bulbless ship. According to this definition, a positive bulb effect corresponds to a power reduction, and vice versa.

In order to separate the different friction resistance components of ships without and with bulb in accordance with Froude's method, the total delivered power P_D

$$P_D = P_R + P_F \tag{14}$$

is regarded as composed of a frictional part (index F) and a residual part (index R). If the propulsive efficiency η_D is known, the residual power can be calculated as the difference

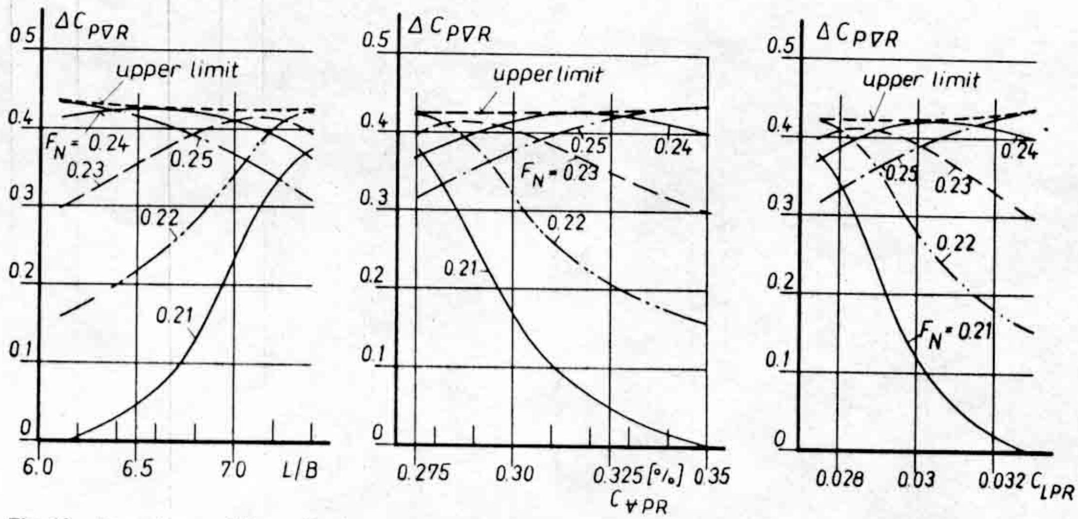

Fig. 10 Dependence of the residual power reduction coefficient on the length/beam ratio, the volumetric parameter, and the length parameter, respectively. Curve parameter is the Froude number. The parameters C_{ABT}, C_{ABL}, C_{BB}, C_{ZB}, and B_{MS}/T_{MS} are constant

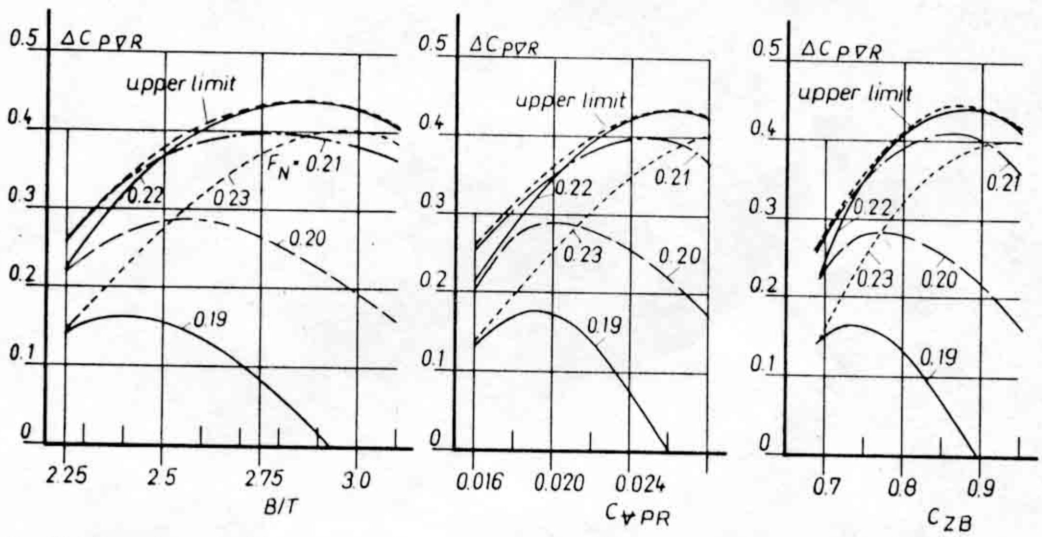

Fig. 11 Dependence of the residual power reduction coefficient on the beam/draft ratio, the volumetric parameter, and the depth parameter, respectively. Curve parameter is the Froude number. The parameters L_{PP}/B_{MS}, L_E/B_{MS}, C_{ABT}, C_{ABL}, C_{LPR} and C_{BB} are constant

between total and frictional power, and a residual power reduction factor

$$\Delta P_R^* = 1.0 - P_{Rw}/P_{Ro} = 1.0 - (P_{Dw} - P_{Fw})/(P_{Do} - P_{Fo}) \quad (15)$$

can be defined.

The relationship between effective P_E and delivered power is

$$P_D = P_E/\eta_D = (P_{ER} + P_{EF})/\eta_D \quad (16)$$

With the frictional power P_{EF} calculated by the International Towing Tank Conference (ITTC) 1957 line

$$P_{EF} = C_F\left(\frac{\rho}{2} V_S^3 \cdot S\right) \quad (17)$$

the residual power is

$$P_R = P_{ER}/\eta_D = P_D - P_{EF}/\eta_D \quad (18)$$

With equations (16) to (18), the residual power reduction factor becomes

$$\Delta P_R^* = 1.0 - \frac{P_{Dw}\eta_{Dw} - P_{EFw}}{P_{Do}\eta_{Do} - P_{EFo}} \times \frac{\eta_{Do}}{\eta_{Dw}} \quad (15a)$$

A separation of the various bulb effects is not possible in this way.

The propulsive efficiency η_D is a function of hull form and speed and should be known for the analysis of the model test results. Moreover, for ships without and with bulb, the propulsive efficiencies are generally not equal, but it is $\eta_{Dw} > \eta_{Do}$ in the beneficial speed range of the bulb ship. Unfortunately, from most of the propulsion test results, η_D could not be estimated. Therefore, as a first step in simplification of the reanalysis, a constant η_D has to be chosen for ships without and with bulb. The mistake is small if in the calculation of the residual power reduction factor by equation (15a), the condition $\eta_{Dw} = \eta_{Do}$ is assumed. In general, the relations

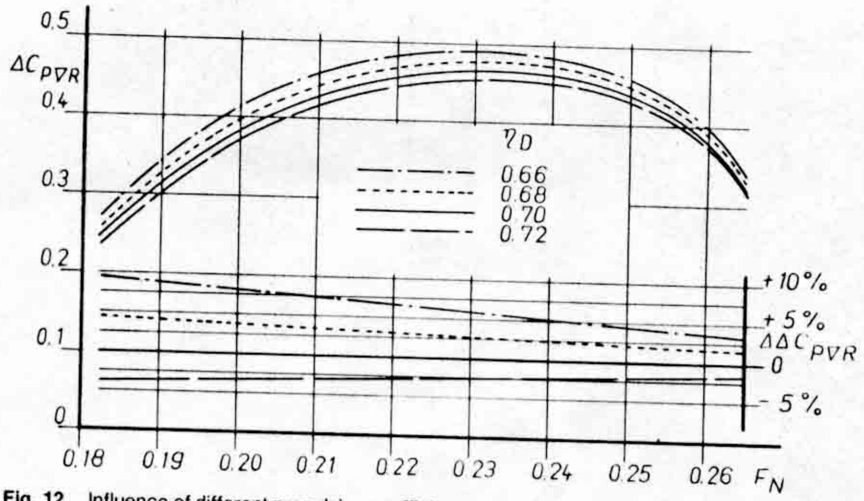

Fig. 12 Influence of different propulsive coefficients on the residual power reduction coefficient, shown with the ship-bulb combination No. 7 of Table 2

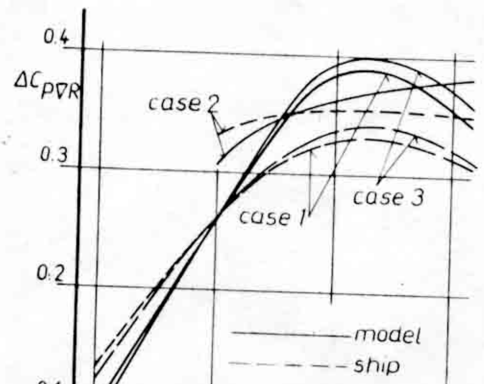

Fig. 13 Comparison of the residual power reduction coefficients from full-scale and model-scale measurements (for main particulars, see Table 1)

$$P_{EFw} > P_{EFo} \quad (\text{because } S_w > S_o)$$

$$P_{Dw} < P_{Do}$$

$$\eta_{Dw} > \eta_{Do}$$

and

$$P_{Dw}\eta_{Dw} > P_{Dw}\eta_{Do}$$

hold. Consequently the numerator difference of equation (15*a*) is

$$P_{Dw}\eta_{Dw} - P_{EFw} > P_{Dw}\eta_{Do} - P_{EFw}$$

but because of

$$\eta_{Do}/\eta_{Dw} < 1.0$$

it is

$$(P_{Dw}\eta_{Dw} - P_{EFw})\frac{\eta_{Do}}{\eta_{Dw}} \approx (P_{Dw}\eta_{Do} - P_{EFw})$$

Therefore, the residual power reduction factor used here is

$$\Delta P_R^* = 1.0 - (P_{Dw} - P_{EFw}/\eta_D)/(P_{Do} - P_{EFo}/\eta_D) \quad (15b)$$

Because a few propulsive efficiencies are known only in the collected routine test results, in a second step of simplification an η_D has to be defined that should be constant for all ship-bulb combinations within the whole range of block coefficient C_B. From the scarce experimental results and practical experience

$$\eta_D = 0.7$$

appeared to be a very good mean value. For normal ships, η_D is between 0.6 and 0.8. Therefore, it is important to test the consequences of divergence of η_D from the mean value 0.7 on the residual power reduction coefficient $\Delta C_{P\nabla R}$. As shown in Fig. 12, a change in η_D of ±3 percent affects at low Froude numbers, F_N, a change in $\Delta C_{P\nabla R}$ of only ±4 percent; at higher F_N of only ±1.5 percent.

Further analysis is facilitated by the introduction of dimensionless coefficients as follows. To eliminate influences of the ship hull form, the power displacment coefficient

$$C_{P\nabla} = P/(\rho/2V_S^3\sqrt[3]{\nabla_{WL}^2}) \quad (19)$$

is chosen. This leads to a residual power coefficient

$$C_{P\nabla R} = P_D/(\rho/2V_S^3\sqrt[3]{\nabla_{WL}^2}) - C_F S/(\eta_D\sqrt[3]{\nabla_{WL}^2}) \quad (20)$$

and with friction law

$$C_F = 0.075/(\log R_N - 2.0)^2 \quad (21)$$

to the bulb effect related to the residual power coefficient, that is, to the residual power reduction coefficient

$$\Delta C_{P\nabla R} = 1.0 - C_{P\nabla R\ with}/C_{P\nabla R\ without} \quad (22)$$

Finally, it should be mentioned that in the reanalysis a form factor k is not considered.

The residual power reduction coefficient can be scaled directly to full-scale ship. Figure 13 shows the results of measurements at ship [35] and model scale. The slight sea-wave influence on full-scale measurements is eliminated. That the amounts do not coincide totally might depend on the different trims of the forms without and with bulb. Table 1 gives the main particulars of the ships. In case 3, the delivered power of the bulbless ship is converted to a draft T = 6.57 m (21.55 ft) by aid of the Admiralty formula.

Design charts

The analysis of the many experimental results is sorted out by C_B-collectives in which many bulb ship forms with nearly the same block coefficients are collected. There are so many design charts that only the case of $C_B = 0.7$ is presented here. The variation of the residual power reduction coefficient by equation (22) of each ship form

$$\Delta C_{P\nabla R} = F(F_N, \text{bulb form}) \tag{23}$$

has been calculated and presented as a function of Froude number F_N. The curve parameter is the bulb form (Fig. 14). From these curves it is possible to derive cross curves for all six bulb parameters, which are collected in Table 2 together with some other main parameters of the ship-bulb combinations. The derivation and fairing of these cross curves (Fig. 15–20) naturally are not totally without problems, because at only one variable bulb parameter the other five parameters are regarded as constant. This assumption is correct in only a few cases for some parameters; in most of the cases, all parameters alter simultaneously. Therefore, each diagram contains an upper limit curve which indicates the maximum possible improvement due to a bulb. Figures 21 and 22 show that the way of analysis and construction of design diagrams is justified. In these figures, theoretical and the corresponding experimental results which are evaluated in the same manner are compared [31]. Even if the optimistic theoretical results are not achieved in the experiments, the tendencies are at least represented correctly.

The diagrams of Figs. 16–20, which are derived from the

Table 1 Main particulars of ships without (Ship 1) and with bulbous bow. (See Fig. 13; $\Delta T_T/L_{PP}$ is the related trim)

	case 1		case 2	
	ship 1	ship 3	ship 1	ship 2
T_{MS} [m]	5,98	6,57	5,96	5,68
$\Delta T_T / L_{PP}$	0,129 %	1,17 %	0,129 %	1,05 %
δ_{PP}	0,7842	0,7869	0,7842	0,7813
φ_V	0,8370	0,7857	0,8370	0,7832
L_{WL} / B_{MS}	6,933	7,092	6,933	7,087
B_{MS} / T_{MS}	4,550	4,140	4,550	4,645
L_{PR} / L_{PP}	–	0,0205	–	0,0205
B_B / B_{MS}	–	0,1397	–	0,1397
Z_B / T_{FP}	–	0,5570	–	0,6260
A_{BT} / A_{MS}	–	0,0946	–	0,0954
A_{BL} / A_{MS}	–	0,1056	–	0,1070
$\nabla_{PR} / \nabla_{WL}$ %	–	0,1725	–	0,1773

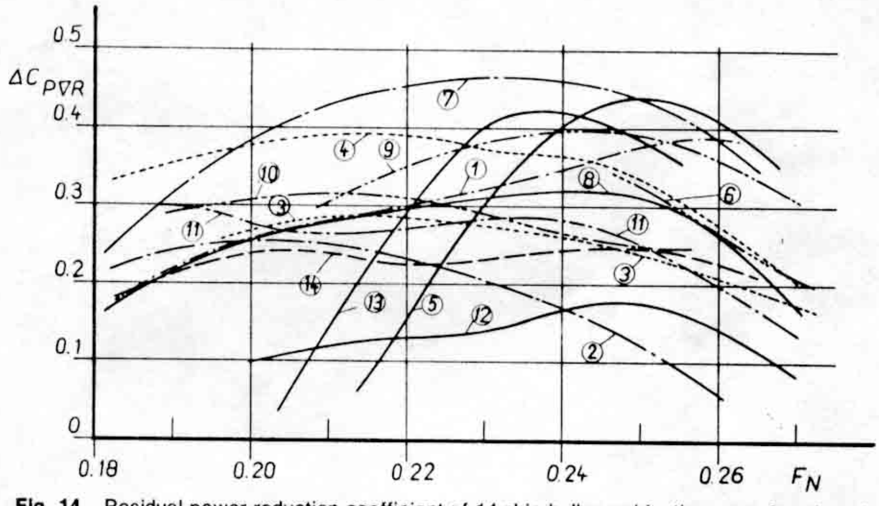

Fig. 14 Residual power reduction coefficient of 14 ship-bulb combinations as a function of Froude number. Basic diagram for Figs. 15–20 (for main parameters, see Table 2). Curve parameter is the bulb form

Table 2 Main parameters of ship-bulb combinations of the data collected with $C_B = 0.7$ (see Fig. 14)

	Model	1	2	3	4	5	6	7	8	9	10	11	12	13	14
without bulb	C_B	0,6846	0,689	0.6891	0,6918	0,6924	0,6963	0,6967	0.6967	0.6970	0.7004	0,7033	0.7145	0.7227	0.7266
	C_{WL}	0,8173	0,8389		0.7931	0.7762				0.8058			0.8449	0,7994	
	C_M	0.9829	0.9868	0.8785	0.9938	0.9845	0.9916	0,9733	0,9733	0.9868	0.9920	0.9829	0,9949	0.9845	0.9816
	C_{PE}	0,6865		0,7211	0.6919	0.6994	0.7148	0,7234	0.7234	0,6703	0.6452	0.6662	0,6985	0,6994	0.6945
	L_{WL}/B	7.5489	6.088	5.293	6.4997	6.0061	5.702	6.094	6,094	7.2094	7.315	8,171	6.7414	6.7170	6.517
	B/T	2.1539	3.006	3.153	2.8285	3.0402	2.972	3.114	3,114	2.2575	2.491	2.168	2.3259	3.0402	2.724
	L_E/B	3.774	3.044	2.0472	2.880	2.4561	2.855	2.978	2.978	3.1634	2.907	3.501	2.9250	2.4561	2.514
with bulb	C_B	0,6846		0.6935	0,6977	0,7069	0,7026	0.7055	0,7028	0.7062	0.7047	0.7070	0,7194	0.7373	0.7317
	L_E/B	3.774		2.244	3.4639	2.6587	3.063	3.240	3.197	3.4162	3.1100	3.673	3.4639	2.6587	2.722
	C_{LPR}	0.0370	0.0299	0.0433	0.0329	0.0330	0.0363	0.0440	0.0368	0.0381	0.0251	0.0258	0.0329	0.0296	0.0330
	C_{BB}	0.1554	0.0840	0.1762	0.1821	0.1798	0,1717	0,2091	0,1746	0.1538	0.1463	0.1351	0.1821	0.1798	0.1734
	C_{ZB}	0.6377	0.6580	0.5612	0.6730	0.9333	0.5938	0.5587	0.5852	0.5810	0.6309	0.4267	0.5530	0.9333	0.5652
	C_{ABT}	0.1008	0.0465	0.1103	0.1056	0.1090	0.1035	0.1367	0.1061	0.1032	0.0956	0,0802	0.0879	0.1090	0.1008
	C_{ABL}	0,1829	0,1258	0.1286	0.1498	0.1516	0.1237	0.1696	0.1284	0.1832	0.1096	0.1268	0,1230	0.1516	0.1157
	$\% C_{\nabla PR}$	0,3356	0,1350	0,4015	0.3929	0.3606	0.2871	0.5878	0.3618	0,3120	0.2246	0.1819	0,3118	0.3096	0.2975
	$\% C_{\nabla tot}$	1.2026	0.3782	0.6466	0,8712	0.3713	0.9071	1.2547	0.8462	1.3183	0.6207	0,5177	0.6936	2.0363	0.6957
	$\% C_{S tot}$	3.0572	1.4159	2.1905	3.0228	2.8112	3.0283	3.0692	2.4268	2.5054	2.3123	1.8757	2.6458	2.4545	2.3753

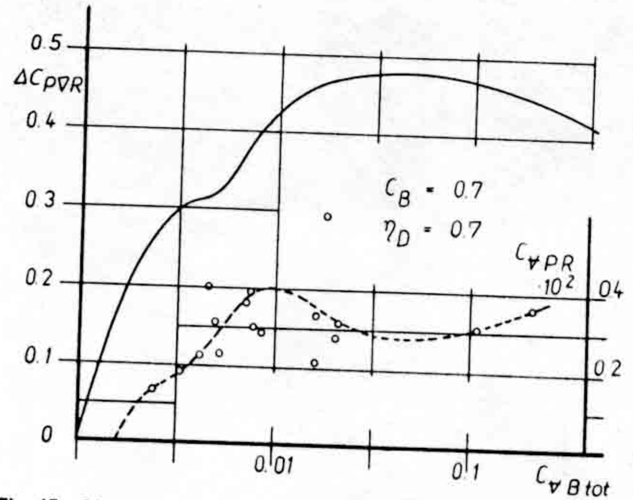

Fig. 15 Maximum residual power reduction coefficient as a function of the volumetric parameter of total bulb volume (derived from Fig. 14)

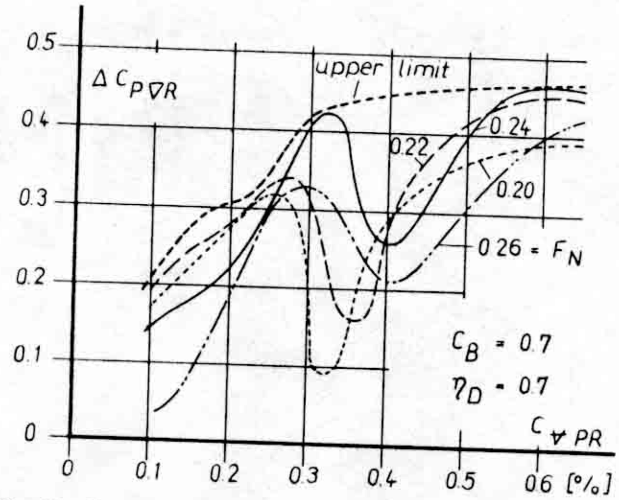

Fig. 16 Residual power reduction coefficient as a function of the volumetric parameter (derived from Fig. 14). Curve parameter is the Froude number

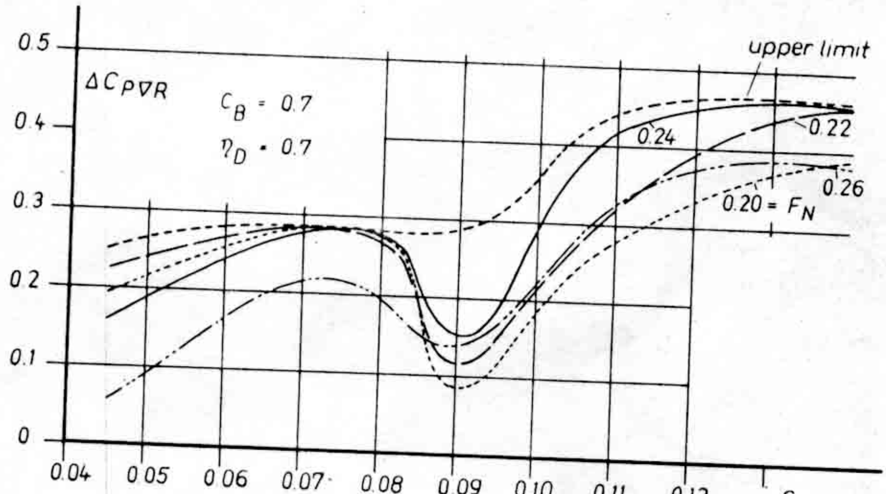

Fig. 17 Residual power reduction coefficient as a function of the cross-section parameter (derived from Fig. 14). Curve parameter is the Froude number

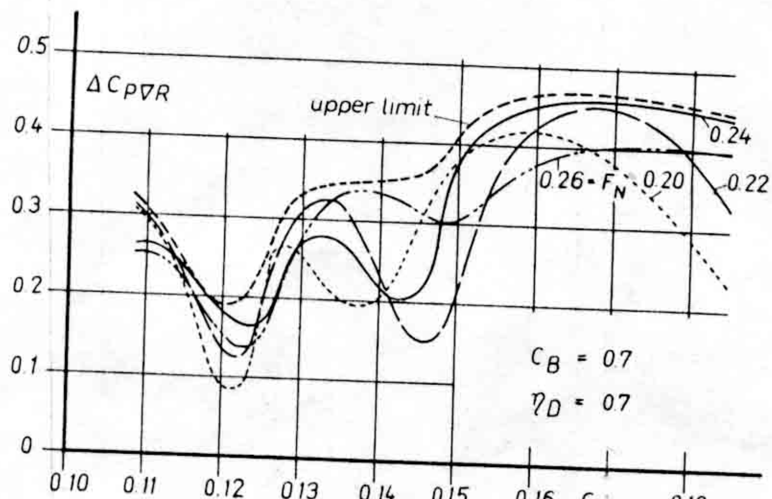

Fig. 18 Residual power reduction coefficient as a function of the lateral parameter (derived from Fig. 14). Curve parameter is the Froude number

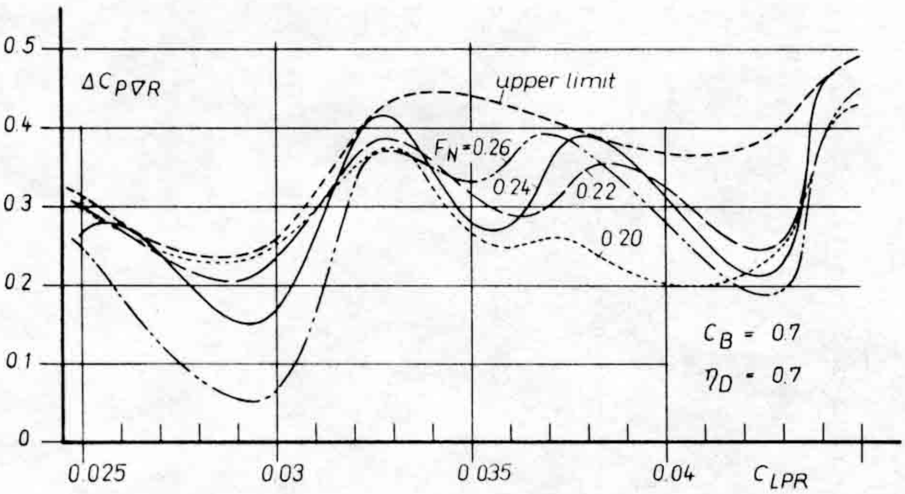

Fig. 19 Residual power reduction coefficient as a function of the length parameter (derived from Fig. 14). Curve parameter is the Froude number

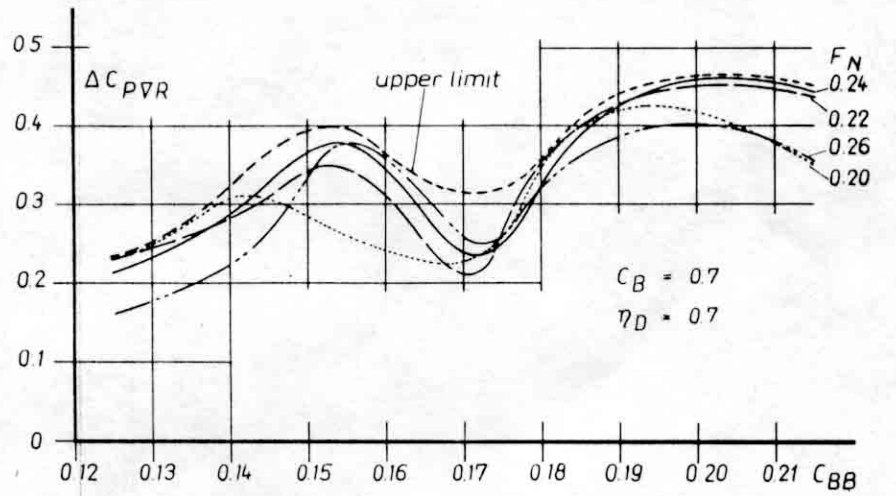

Fig. 20 Residual power reduction coefficient as a function of the breadth parameter (derived from Fig. 14). Curve parameter is the Froude number

diagram of Fig. 14 for $C_B = 0.7$, represent the correlations between bulb parameters and power gain. Regions may clearly be recognized in which certain bulb parameters are unfavorable and which are to be avoided.

The use of the diagrams follows from their derivation. Interpolations are permitted inside the parameter ranges shown, while extrapolations should be avoided. If the main dimensions of a ship are fixed and a bulb is to be fitted, then the estimation of bulb parameters and the power reduction due to this bulb is possible by means of the design charts of the corresponding block coefficient C_B. For this purpose, only the main-hull particulars, L_{PP}, B_{MS}, T_{MS}, and C_B as well as the Froude number F_N, are required. For a given bulb parameter—which can be any of the six parameters—it is possible to read in the respective design chart at the curve of the known Froude number F_N the residual power reduction factor $\Delta C_{P\nabla R}$. With this $\Delta C_{P\nabla R}$, the remaining bulb parameters are estimated in the other diagrams at the corresponding F_N-curve. Except for the configuration of the bulbous forebody, the problem is solved, because, for F_N = constant, all six bulb parameters are assigned to a constant $\Delta C_{P\nabla R}$.

If C_B, L_{PP}/B_{MS}, and B_{MS}/T_{MS} of the bulbless ship are inside the ranges of the analyzed ship-bulb combinations, for example, of Table 2, then the residual power reduction factor $\Delta C_{P\nabla R}$ yields the wanted residual power gain. If departures from the main-hull parameters appear, the $\Delta C_{P\nabla R}$ is a good approximate value. Except for the beam/draft ratio, the influence of C_B and L_{PP}/B_{MS} deviations is small, so that a special correction is not necessary for these parameters. A general correction formula so far does not exist.

If the delivered power for the bulbless ship is known, then the required power of the bulb ship can be calculated by the following formula:

$$P_D = \{(1.0 - \Delta C_{P\nabla R})C_{P\nabla Ro} + [C_F S/(\eta_D \sqrt[3]{\nabla^2_{WL}})]\}\frac{\rho}{2} V_S^3 \sqrt[3]{\nabla^2_{WL}} \quad (24)$$

where the residual power coefficient $C_{P\nabla Ro}$ of the bulbless ship has to be estimated with $\eta_D = 0.7$ according to equation (20). For unknown delivered power of the bulbless ship, in the project phase, the required power can be calculated by the following formula:

$$P_D = [(1.0 - \Delta C_{P\nabla R})C_R + C_F + \Delta C_F]\frac{\rho}{2} V_S^3 S \quad (25)$$

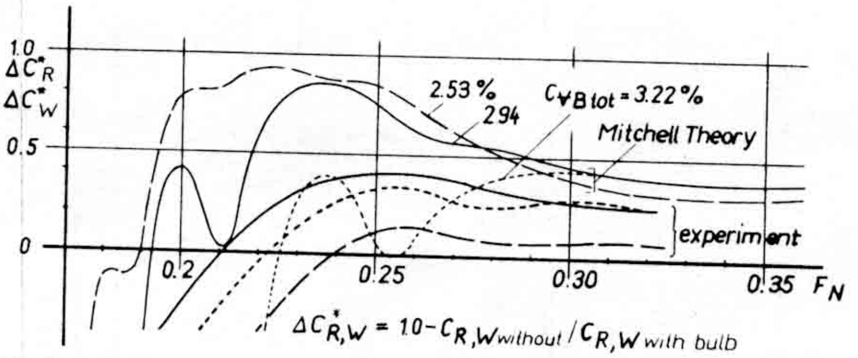

Fig. 21 Bulb effect on residual or wave resistance coefficient, respectively, as a function of Froude number. Comparison of theoretical and experimental results of elementary ship form (2,4,6,0.72,1.0). Curve parameter is the volumetric parameter of the total bulb volume. The experimental results are evaluated with a form factor $k = 0.205$

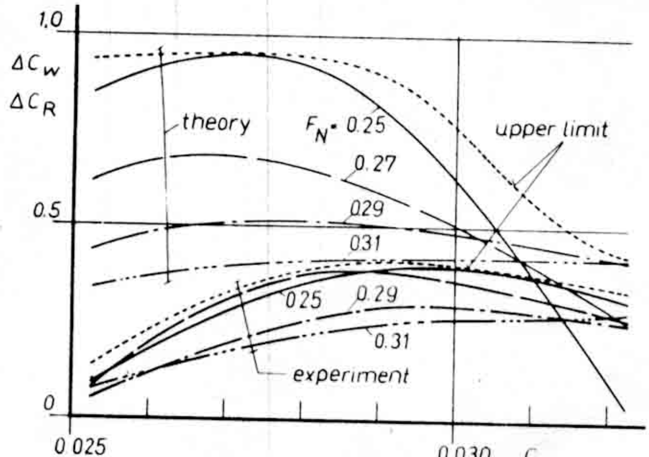

Fig. 22 Bulb effect on residual or wave resistance, respectively, as a function of the volumetric parameter of the total bulb volume (derived from Fig. 21). Curve parameter is the Froude number

where C_R can be estimated by one of the common procedures (for example, Taylor-Gertler [35], or Guldhammer [36]).

If several bulb parameters are known (this includes also the judgment of a given bulb), then the estimation of the power gain by means of the diagrams is problematic, because the relation of the single values is hardly guaranteed in such a way that all known bulb parameters result in the same $\Delta C_{P\nabla R}$ at constant Froude number. By using the volumetric parameter $C_{\nabla PR}$ as the main parameter connected with a possible consideration of C_{ABT} and C_{ABL}, the diagrams can be used in such cases for bulb design or for a judgment.

It appears tempting to use the diagrams to design an optimal bulb by taking the parameters in accordance with their maximum reduction effect only. This procedure cannot be recommended, because all six optimal bulb parameters chosen in this way do not generally coincide with those of a concrete bulb of the analyzed test data.

To judge the effect of a bulb change on the required power of a bulb ship, the diagrams can be used to assist in decision-making. By their aid, the tendency of parameter changing can be detected which an alteration of shape does or does not suggest. Even in their imperfect form, the design charts facilitate the decision for an application of a bulbous bow. But they do not substitute for the model test, because the actual power requirement for a project can be measured by experiment only.

From Figs. 23 to 26, the bulb parameters can be estimated if at first instance the power consumption is of no interest. These figures show the relationship of the different bulb parameters to each other for the ship-bulb forms which have been analyzed within the research project. The usual bulb parameter ranges are marked by upper and lower dotted lines.

Aspects of bulb design

In the preceding sections, it has been shown that a well-dimensioned bulbous bow improves the performance of a ship in many ways by smoothing the flow around the forebody and by reducing the wavemaking resistance. In a particular case, the decision for or against a bulbous bow is the matter of a cost-effectiveness analysis [11], which is not the subject of this paper.

In general it may be stated that a hydrodynamically good main hull with low wavemaking does not need a bulbous bow in any case. But ships with pronounced bad wavemaking should always be fitted with a bulb. Practical points of view will decide whether an additive or an implicit bulb is to be provided for. For ships already built, an additive bulb will in general be the best solution, while for a new design an implicit bulb might be advantageous.

The shaping of a bulbous bow, that is, the longitudinal and depth distribution of the bulb volume in proportion to the bulb parameters, can be described only in a qualitative way. Although for a concrete longitudinal distribution of bulb volume, the knowledge of the wave pattern of the bulbless ship is an important decision-making aid, in the preliminary project phase this information is usually not available. But even without this information it is possible to indicate general guiding rules for shaping a bulbous bow. Essentially they are related to

- type of ship (full or slender),
- service speed (slow or fast),
- frequency of draft alteration at FP (large draft variation or defined C_{WL} and ballast draft), and
- main operation area of the ship (for example, with much heavy seaway or drift ice).

A specific ship-bulb form shows optimum performance only at design conditions. At off-design conditions its performance may be poor.

For the distribution for the bulb volume, the following three rules are important:

1. Deeply emerged volume is of little effect.
2. Longitudinally concentrated volume near to the free surface increases the interference effect.
3. Longitudinally distributed volume near to the free surface influences the momentum deflection.

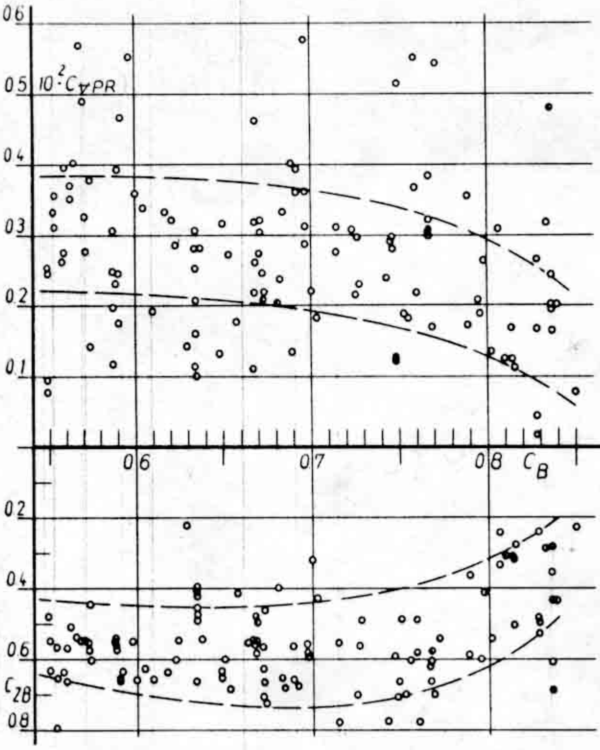

Fig. 23 Volumetric and depth parameter versus block coefficient

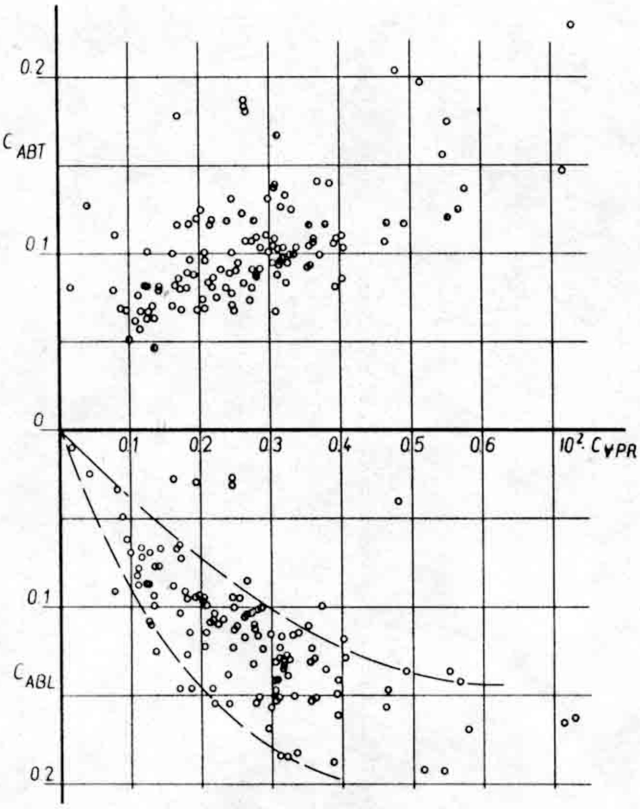

Fig. 25 Cross-section and lateral parameter versus volumetric parameter

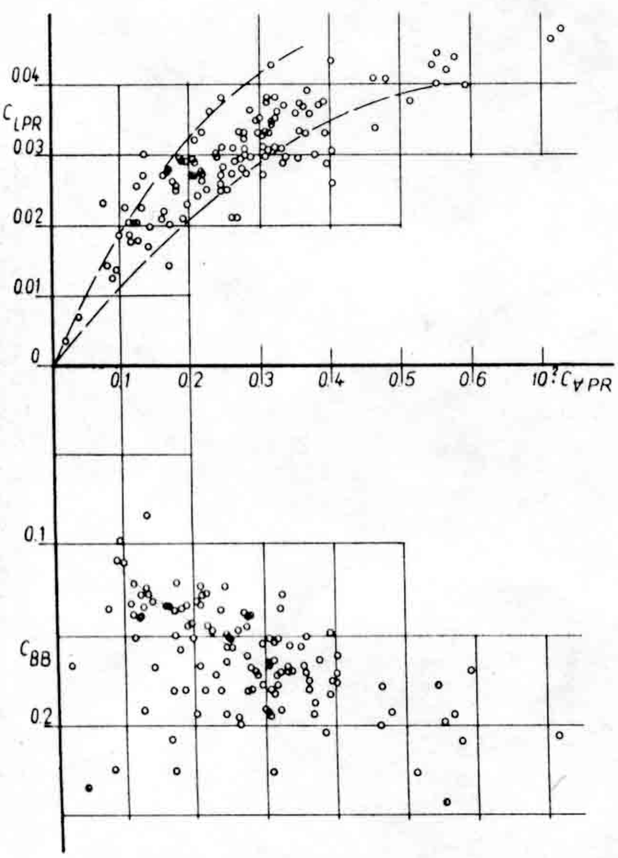

Fig. 24 Length and breadth parameter versus volumetric parameter

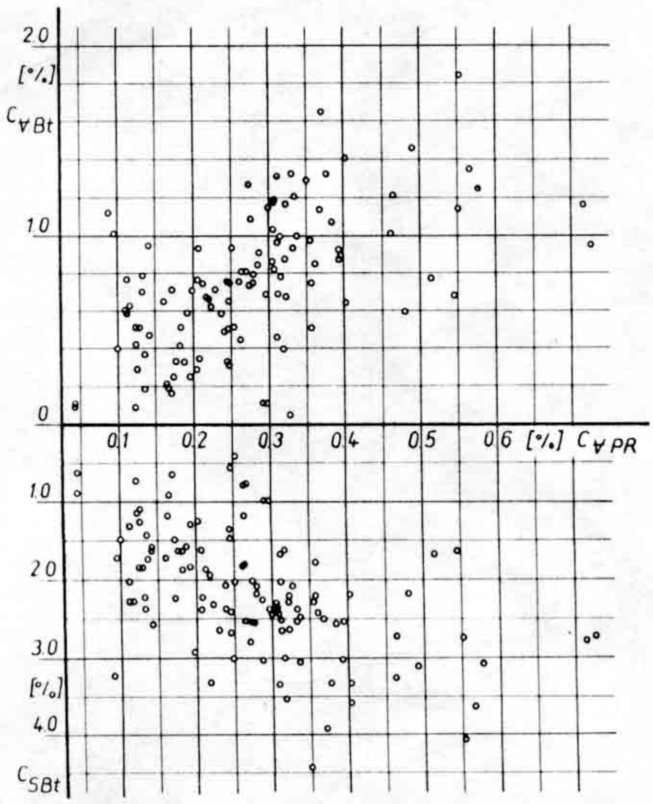

Fig. 26 Total increase of the volume ($C_{\nabla Bt}$) and the wetted surface (C_{SBt}) of the main hull due to a bulbous bow versus volumetric coefficient $[C_{\nabla Bt} = (\nabla_{WLw} - \nabla_{WLo})/\nabla_{WLo};\ C_{SBt} = (S_w - S_o)/S_o]$

The waterlines of the bulb nose should be streamlined but not circular, in order to avoid separation [33].

For ships with a strong wavemaking tendency, the bulb volume should be concentrated in the longitudinal direction, where the upper part of the bulb body at the *FP* should not be located above the C_{WL}. The integration of bulb and ship can be straight-lined ([3], Rule 4). The fairing volume plays a subordinate role. The maximum width of the bulb can be situated in front of the forward perpendicular. At such a bulbous bow it may happen, of course, that cavitation occurs. This problem is not treated here.

For ships with much wave-breaking, the bulb volume should be distributed well in the longitudinal direction. The upper part of the bulb body can reach to the peak of the bow back-wave of the bulbless ship [34]. A well-formed laterally and forward-inclined bulb ridge avoids the breaking of the bow back-wave. The fairing volume plays an important role. The upper part of the bulb should be faired well into main hull in order that the tail water of the bulb ridge interferes well with the remaining bow wave. In the lower part of the bulb, the waterlines should have small angles of entrance if the bulb is to emerge high under ballast conditions. Due to the danger of separation in this area, the fairing of the waterlines should not be too hollow.

Bulb-type recommendations

The O-type is suitable for full as well as for slender ships. It fits well with U- and V-types of foreship sections and offers space for sonar equipment. The lens-type should be chosen for ships which often operate in heavy seas, because it is less susceptable to slamming.

The Δ-type is good for ships with large draft variations (tramp ships) and U-type foreship sections. The effect of the bulbous bow decreases with increasing draft, and vice versa; but in heavy seas the danger of slamming increases with decreasing draft.

The ∇-type can be provided for all ships with well-defined C_{WL} and ballast draft. It is easily faired into V-shaped forebodies and has in general good seakeeping performance. In the fully submerged condition, its damping effect is very high.

In all cases, the bulb should not emerge in the ballast condition so that its most forward point, B (Fig. 3), lies on the water surface. The individual resistance of the bulb body in this condition would be higher than its net efficiency.

Summary

Today the bulbous bow has asserted itself as an elementary device in practical shipbuilding. But the existing design methods are not sufficient for power estimation of a bulb ship and for modern bulb design. A well-dimensioned bulb improves most of the properties of a ship. Therefore, qualitative and quantitative guiding rules are necessary for its beneficial application.

Compared with the indirect influence of a bulbous bow on thrust deduction and wake fraction, the bulb also influences directly the wake distribution in the propeller plane. Except for the strongly damped pitching motion, the bulb ship has the same seakeeping qualities as a bulbless ship up to Beaufort 6. Therefore, regardless of seakeeping aspects, the bulb design may be carried out in view of the smooth-water performances only. In navigation in ice, the bulbous bow has proved to be advantageous.

The most important effect of a bulbous bow is its influence on the different resistance components and, consequently, on the required power consumption. By attenuation of the bow wave system, the bulb reduces the wavemaking as well as the wave-breaking resistance.

Two main bulb effects which are very important for bulb design are defined as the interference and the breaking effects. The interference effect expresses the resistance change due to the interfering free wave systems of main hull and bulb. For slender, fast ships, it gives the main proportion to the total bulb effect. Its amount depends on bulb volume and the longitudinal position of the bulb center. The wave-breaking effect includes the energy loss by breaking of too steep bow waves and gives the main contribution to the total bulb effect of full, slow ships. Its amount depends on well-distributed bulb volume in the longitudinal direction. Both bulb effects are Froude number dependent.

For bulb design, six bulb parameters are introduced, of which the volumetric, the cross-section, and the length parameter are the most important. The influence of bulb parameters on the different bulb effects is discussed in a qualitative manner, supported by the linearized theory of wave resistance and by some experimental results. This knowledge is important for the shaping of the bulb body according to the bulb parameters.

A quantitative design method is presented together with the necessary design data. The data are derived from an analysis of routine test results of the two German model basins. Most of the usable data were propulsion rather than resistance test results. Therefore, according to Froude's method, a residual power reduction coefficient is defined which can be scaled directly to the full-scale ship. The variation of this coefficient for each ship-bulb combination has been calculated and presented as a function of Froude number. From these curves the design charts are derived—for each bulb parameter, one diagram. From the multitude of diagrams, only one example is depicted. The calculation of the required power of the bulb ship is described. General guiding rules for shaping a bulbous bow are given.

The design guidelines have been successfully applied on various occasions.

References

1 Gawn, R. W. L., "Historical Notes and Investigations at the Admiralty Experiment Works," Torquay; *Trans.* TINA, 1941.

2 Eggert, E. F., "Form Resistance Experiments," TRANS. SNAME, Vol. 43, 1935; "Further Form Resistance Experiments," TRANS. SNAME, Vol. 47, 1939.

3 Wigley, W. C. S., "The Theory of the Bulbous Bow and its Practical Application," *Trans.* North-East Coast Institution of Engineers and Shipbuilders, Vol. 52, 1935/36.

4 Weinblum, G., *Theorie der Wulstschiffe*, 1935.

5 Inui, T., Takahei, T., and Kumano, M., "Wave Profile Measurements on the Wave-making Characteristics of the Bulbous Bow," *Zosen Kiokai*, Vol. 108, Dec. 1960; also *Journal of the British Ship Research Association*, Vol. 16, 1961.

6 Inui, T. and Takahei, T., "Wave Cancelling Effects of the Waveless Bulb on the High-Speed Passenger Coaster (*Kurenai Maru*, Part I-III)," *Zosen Kiokai*, Vol. 110, Dec. 1961.

7 Kerlen, H., "Entwurf von Bugwülsten für völlige Schiffe aus der Sicht der Praxis," *HANSA*, No. 10, 1971.

8 Kracht, A., "Theoretische und experimentelle Untersuchungen für die Anwendung von Bugwülsten," *FDS-Bericht*, No. 36, 1973.

9 Kracht, A., "Der Bugwulst als Entwurfselement im Schiffbau," *STG-Jahrbuch*, Band 70, 1976.

10 Takahei, T., "Bulbous Bow Design for Full Hull Forms," *Trans.* Society of Naval Architects of Japan, Vol. 119, May 1966.

11 Schneekluth, H., "Kriterien zur Bugwulstverwendung," *STG-Jahrbuch*, 1975.

12 Taniguchi, K. and Tamura, K., "Study on the Flow Patterns Around the Stern of a Large Full Ship," *Mitsubishi Technical Review*, Vol. 7, No. 4, 1971.

13 Tatinclaux, J.-C., "Effect of Bilge Keels and a Bulbous Bow on Bilge Vortices," IIHR Report No. 107, Feb. 1968.

14 van Lammeren, W. P. A. and Muntjewerf, J. J., "Research on

Bulbous Bow Ships. Part II. A Still Water Performance of a 24000 DWT Bulkcarrier with a Large Bulbous Bow," *International Shipbuilding Progress*, Vol. 12, 1965, p. 459.

15 van Lammeren, W. P. A. and Pangalila, F. V. A., "Research on Bulbous Bow Ships. Part II B," *International Shipbuilding Progress*, Vol. 13, No. 137, Jan. 1966.

16 Wahab, R., "Das Verhalten eines schnellen Frachtschiffes mit konventionellem Bug und mit Wulstbug im Seegang," *STG-Jahrbuch*, Band 60, 1966, p. 233.

17 Ochi, K., "Model Experiments on the Effect of a Bulbous Bow on Ship Slamming," DTMB-Report 1360, Oct. 1960.

18 Frank, W., "The Heave Damping Coefficients on Bulbous Cylinders, Partially Immersed in Deep Water," *Journal of Ship Research*, Vol. 11, No. 3, Sept. 1967, p. 151.

19 Dillon, E. S., Lewis, E. V., and Scott, E., "Ships with Bulbous Bows in Smooth Water and in Waves," TRANS. SNAME, Vol. 63, 1955, p. 726.

20 Wahab, R., "Research on Bulbous Bow Ships. Part I B," *International Shipbuilding Progress*, No. 142, 1966, p. 181.

21 Brühl, W., "Der Bugwulst in der Eisfahrt," *Schiff und Hafen*, Vol. 23, No. 1, 1971, p. 17.

22 Yim, B. and Shih, H. H., "Minimum Wave Bulbous Ship Hulls with Parallel Middle Body," Hydronautics Inc. Technical Report 117-9.

23 Baba, Eiichi, "Analysis of Bow Near Field of Flat Ships," Mitsubishi Technical Bulletin No. 97, 1975.

24 Baba, Eiichi, "Blunt Forms and Wave Breaking," SNAME, First Ship Technology and Research (STAR) Symposium, Washington, D.C., Aug. 1975.

25 Wieghardt, K., "Viscous Resistance," 13th ITTC, Vol. 1, 1972, p. 83.

26 Eckert, E. and Sharma, S. D., "Bugwülste für langsame, völlige Schiffe," *STG-Jahrbuch*, 1970, p. 129.

27 Eggers, K., "Über die Ermittlung des Wellenwiderstandes eines Schiffsmodells durch Analyse seines Wellensystems," *Schiffstechnik*, Vol. 9, 1962, p. 46.

28 Ward, L. W., "A Method for the Direct Experimental Determination of Ship Wave Resistance," Doctoral Dissertation submitted to the Faculty of Stevens Institute of Technology, Hoboken, N. J., May 1962.

29 Schmidt-Stiebitz, H., "Systematische Erfassung von örtlich am Schiff anzubringende Stau- bzw. Unterdruck erzeugende Elemente zwecks Verringerung der Wellenhöhe und damit des Wellenwiderstandes," *Schiff und Hafen*, Vol. 12, 1960, p. 746.

30 Dagan, G. and Tulin, M. P., "Bow Waves Before Blunt Ships," Hydronautics, Inc., Research in Hydrodynamics Technical Report 117-14.

31 Kracht, A., "Theoretische und experimentelle Untersuchungen über die Verringerung des Wellenwiderstandes gegebener Schiffsformen durch den Bugwulst," Bericht No. 166 des Institutes für Schiffbau, Hamburg, 1966.

32 Kracht, A., "Lineartheoretische Abhandlung über die optimale Verringerung des Wellenwiderstandes gegebener Schiffsformen durch einen Wulst in symmetrischer oder asymmetrischer Anordnung," Bericht No. 183 des Institutes für Schiffbau, Hamburg, 1967.

33 Saunders, M. E., *Hydrodynamics in Ship Design*, Vol. 2, SNAME, 1957.

34 Weicker, D., "Bemerkungen zum Bugwulstentwurf," *Seewirtschaft*, Vol. 3, No. 11, 1971, p. 827.

35 Kerlen, H. and Petershagen, H., "Über den Einfluß eines Bugwulstes auf Leistung und Geschwindigkeit eines völligen Frachtschiffes," *HANSA*, Vol. 105, No. 12, 1968, p. 1063–1067.

36 Gertler, M., "A Reanalysis of the Original Test Data for the Taylor Standard Series," DTMB Report 806, 1954.

37 Guldhammer, H. E., and Harvald, Aa., *Ship Resistance*, Akademisk Forlag, Copenhagen, 1974.

38 Kracht, A., "Weitere Untersuchungen über die Anwendung von Bugwülsten," VWS Bericht No. 811/78, Berlin, 1978.

Discussion

Bohyun Yim, Member

[The views expressed herein are the opinions of the discusser and not necessarily those of the Department of Defense or the Department of the Navy.]

This paper has demonstrated clearly by experimental results from many ships that addition of a bulbous bow can reduce a large portion of the residual resistance of a ship. The charts with the approximate values of important design parameters for bulbous-bow ships will be very useful for naval architects. Although we know the mechanism of the bulb effect in the theory of wave resistance, the optimum size, shape, and location of the bulb cannot be obtained accurately because of the weakness in the theory of wave resistance. We all know well that the present linear theory cannot accurately predict the resistance of oceangoing ships. This is why experimental results are valuable in ship design. However, it is obvious that we have to make full use of theoretical knowledge in order to have a better design.

In bulb design, we recognize that there are two types of bulb: doublet type and source type. The former reduces the sine-component of elementary ship waves while the latter reduces the cosine-component of elementary ship waves. Although normal ships with relatively large entrance angles have dominating sine waves which require the doublet-type bulb, there are ships with hollow waterlines which require the source-type bulb. That is, the bulb shape depends largely upon the waterline shape near the ship bow. I wonder whether this effect is reflected in the charts shown in the present paper? Block coefficient and Froude number are not enough to represent ship parameters related to bulb design. In this respect, Yim's[3] simple design method for a bulbous bow for a particular ship and design speed may be useful.

At the David W. Taylor Naval Ship R&D Center, several bulbs designed by Yim's method have been tested and satisfactory results obtained. Because the method uses linear theory, the computed bulb size is sometimes slightly larger than optimum, yet it gives very useful guidance.

[3] Yim, Bohyun, "A Simple Design Theory and Method for Bulbous Bows of Ships," *Journal of Ship Research*, Vol. 18, No. 3, Sept. 1974, pp. 141–152.

Eiichi Baba, Member

The design charts of bulbous bows provided by the author are suitable especially for ships with relatively small block coefficients. For those ships, the wavemaking phenomena are influenced not only by the entrance part but also by the middle part and the run part, and the form effect on viscous resistance is relatively small. For full forms of $C_B > 0.8$, however, rather large viscous effects are included in the residual resistance component. Therefore, the scale effect is not taken into account in the author's charts. Further, as the author pointed out, for full forms the wavemaking phenomena are mainly depending on the entrance part. Therefore, the characteristic length for the expression of Froude number should be entrance length L_E or ship beam B_{MS} instead of ship total length L_{PP}. The author says that at the preliminary design phase the entrance parameters C_{PE} and L_E are unknown. However, if design charts for full forms based on the entrance parameters are provided, they may be effectively used in the preliminary design phase. Actually at Mitsubishi Heavy Industries a design method of full forms based on entrance parameters has been developed and since 1963 has served as a routine method as outlined in reference [24]. Our design method for full forms is based on the following experimental and practical evidence derived from the analyses of towing test data of more than 200 full forms.

1. For full forms ($v/\sqrt{gL_{PP}} < 0.20$, $C_B > 0.80$) with a