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NAVY DEPARTMENT
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OPTIMUM LOCATION OF THE CENTER OF BUOYANCY OF MERCHANT SHIPS

GÜNSTIGSTE LAGE DES VERDRÄNGUNGSSCHWERPUNKTES VON HANDELSSCHIFFEN

by

Prof. Völker, D. Eng.,
Kharagpur, India

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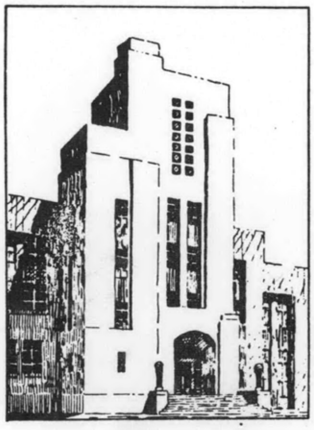

Translated by E.N. Labouvie, Ph. D.

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(Günstigste Lage des Verdrängungsschwerpunktes von Handelsschiffen)

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OPTIMUM LOCATION OF THE CENTER OF BUOYANCY OF MERCHANT SHIPS

Although more than 80 years have elapsed since the establishment of the first model basin, the resistance of even the usual ship forms cannot yet be predicted with sufficient accuracy from the numerous test results of systematic experiments. Essentially, this is probably due to three reasons: First, it often happened that the older ship forms were later found to be unfavorable so that a major part of the test data became practically worthless. Secondly, for a long time several form factors were usually varied at the same time when making systematic form changes so that the effect on resistance of an individual factor, the block coefficient, for instance, could not be determined by itself alone. Thirdly, the more recent developments show that the usual method of applying the model resistance results to the ship may, in some cases, still involve appreciable errors.

At any rate, there gradually began to crystallize a definition of the most essential form factors which was adequate for the time being. These factors are: the fineness ratio $L/D^{1/3}$, the block coefficient δ, the beam/draft ratio B/T, and the location of the center of buoyancy.

This division is but an artifical one, however, since the influence of each factor on resistance changes more or less when the other factors are varied. Nevertheless, the determination of the influence of these factors largely satisfies the requirements of practical ship designing. In the present study, systematic test data will be considered summarily with respect to the location of the center of buoyancy.

Genuine, i.e., exclusive variations of the center of buoyancy always result in typically sinuous resistance curves as in Figure 1. Accordingly, a certain definite location of the center of buoyancy constitutes an optimum location only for a limited speed range. The optimum location for each speed is found by means of cross curves (see Figure 2) which at high Froude numbers generally have steeper branches and at smaller Froude numbers more gentle branches in the upward direction. In some cases, however, the trend of the cross curves may also be wave-like; on occasion, it was possible therefore to observe even two optimum locations of the center of buoyancy.

Test series from Teddington[1] and Göteborg[2] have been evaluated. D.W. Taylor's series offer but few opportunities for evaluation, unfortunately, while numerous other series proved to be useless because other form factors were also varied at the same time as the location of the center of buoyancy. It was possible, moreover, to draw upon the results of extensive evaluations already available, i.e., those of Conn,[1] Ayre,[2] Heckscher,[3] and Helm,[4] all of which indicate optimum locations of the center of buoyancy for those Froude numbers which occur in the case of displacement vessels.

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[1] References are listed on page 6.

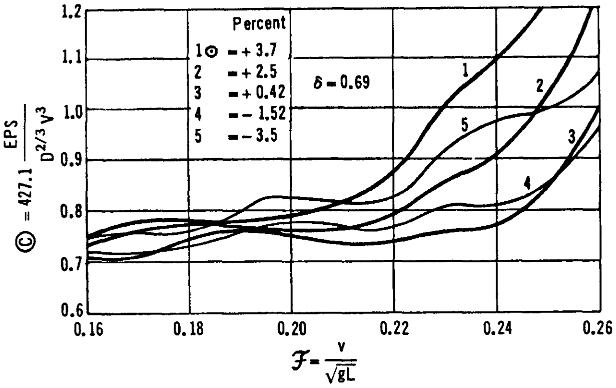

Figure 1 - Resistance Curves for Various Locations of the Center of Buoyancy

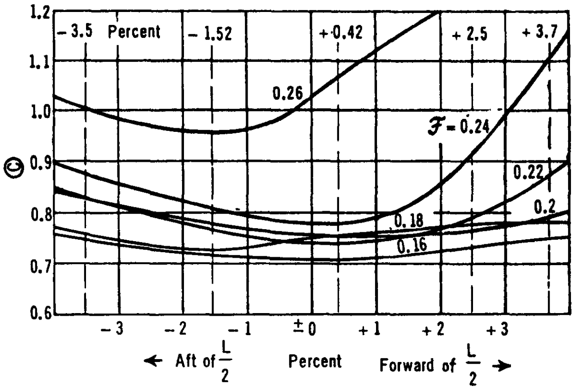

Figure 2 - Cross Curves from Figure 1

The older models of Baker in Teddington were usually varied by decreasing the spacing of sections along the entrance while at the same time increasing those along the run, or vice versa, in such a manner that the parallel middle body or largest section moved forward or aft; in this case, the displacements of the entrances and runs never varied as their lengths, to be sure, but the total length and the total displacement remained the same. The distance of the centers of buoyancy of the tapered parts (entrances and runs) from the ends of the ship remained constant percentages of the lengths of entrance and run, and it proved to be possible to calculate the position of the total centers of buoyancy though Baker merely indicates the variations of the ratio between the length of entrance and the length of run. Today, it has become customary in general to indicate the distance of the center of buoyancy forward or aft of the midship section as a percentage of the length of the ship. The locations of the center of buoyancy in the experiments of Lindblad[1] and Nordström[2], whose forms varied in the same or in a similar manner, as well as those of the above-mentioned evaluations have already been given as percentages.

Figure 3 shows that the optimum locations of the center of buoyancy as a function of the Froude number are widely dispersed. All curves hold for principal proportions that are constant in each case. The block coefficient δ of each curve is indicated for that Froude number for which its value is to be regarded as normal. We chose for this purpose the relation

$$\delta_{pp} = 1.026 - 1.475 \cdot F$$

according to data supplied by Heckscher,[5] a relation which, compared to Ayre's formula[3]

$$\delta_{pp} = 1.08 - 1.68 \cdot F$$

yields somewhat smaller and more probable values for slow vessels. The forms with $\delta = 0.81$, 0.75, 0.69, 0.58, and 0.555 were varied by Baker in the manner indicated above; they show throughout a movement of the optimum position of the center of buoyancy toward the stern as the speeds become relatively higher. The latter form with $\delta = 0.555$ had a pronounced forward shoulder in the curve of sectional areas when the angle of entrance was also small; as a result, the optimum centers of buoyancy lie unusually far aft for all speeds. The form with $\delta = 0.58$ has a fuller entrance with the same afterbody; hence it has a flatter shoulder and its optimum center of buoyancy is located less far toward the stern. Its curve indicates that for slender ships at low speeds the location of the center of buoyancy is obviously of no major importance. The cross curves were very flat and they even indicate two optimum locations of the center of buoyancy far toward the bow and far toward the stern.

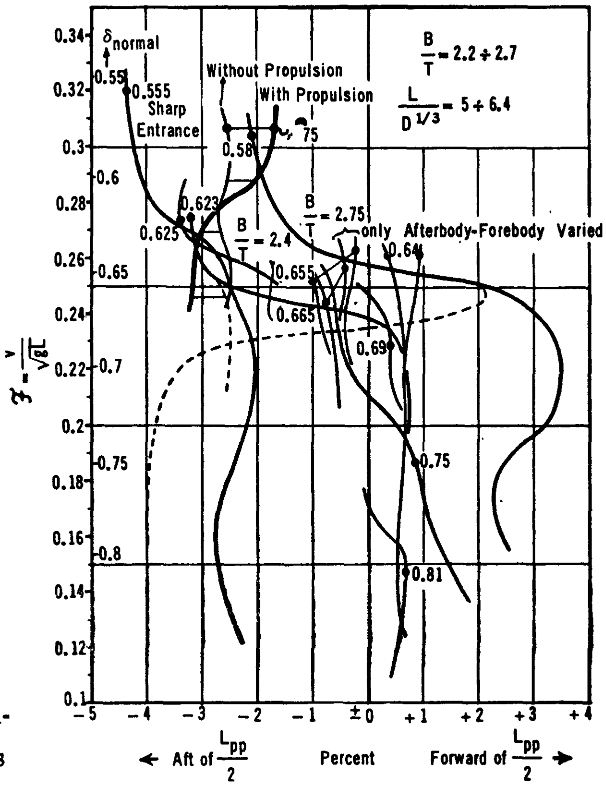

Figure 3 - Optimum Locations of the Center of Buoyancy of Models over the Entire Speed Range

There is another interesting variation by Baker with $\delta = 0.64$; in this, instead of varying the spacing of sections, the form of the entrance or of the run was made finer at the end of the ship and, to compensate for the loss in displacement, it was made fuller at the shoulder. In this case, the center of buoyancy moves also. Here, a pronounced forward shoulder with a hollow waterline is again unfavorable. Hence, with this variation of the forebody the optimum position of the center of buoyancy is relatively far forward, i.e., it is in the forebody entirely if the shoulder is less pronounced and if there is more displacement. The rear shoulder, too, must be easy, i.e., the optimum resistance is obtained when the displacement of the afterbody (for mean contours of the forebody) is shifted as far as possible toward the stern. At low speeds, these differences disappear. Unfortunately, this separate investigation of the position of the center of buoyancy of the forebody and afterbody was not carried on to the point of determining the absolutely most favorable center of total buoyancy by combining the optimum forward with the optimum rear shoulder. Therefore, the use of the data obtained is but a limited one in this case.

Lindblad varied forms with $\delta = 0.665$ and 0.655, the parallel middle body of 16 percent being left unchanged; thereby, he obtained optimum centers of buoyancy located farther aft than Baker's. Only at a smaller draft (beam/draft ratio = 2.75) do they lie again farther forward which is obviously due to the fact that the middle body has been left unchanged.

Recent tests by Nordström in Göteborg with $\delta = 0.625$ showed the optiumn center of buoyancy to be located rather far toward the stern when the spacing of sections was varied consistently, the speed being normal. This (−3.4 percent) strikes our attention at first, and one might be inclined to assume that the forward shoulder of this model may have been too full originally, so that the shoulder became easier and thereby the resistance appreciably reduced as the center of buoyancy moved aft. It is true that the forward shoulder was somewhat pronounced in Nordström's model, but it was not unusual if we consider the fullness in this case.

In Baker's book,[1] however, there is given still another variation of the center of buoyancy for a coastal motor ship with $\delta = 0.623$, i.e., with almost equal fullness. However, the fineness ratio $L/D^{1/3}$ amounted only to 5.04 as compared with 6.35 in the case of Nordström's model and the beam/draft ratio was 2.75 compared with 2.4. In this connection Baker points out, however, that the optimum positions of the center of buoyancy were practically the same for smaller displacements of the model of the coastal motor ship, so that the effect of the $L/D^{1/3}$ and B/T (beam/draft) ratios was but small. The curve of the optimum position of the center of buoyancy of this model (see Figure 3) indicates that the center of buoyancy rapidly moves aft if the speed exceeds $F \approx 0.24$ as in the case of Nordström's model. At $F = 0.275$, it has almost the same position as in Nordström's model. Hence, a position of the center of buoyancy far aft actually would appear to be indicated for $\delta = 0.62$ to 0.63. Upon examining the wave formation, it was seen that in this case, i.e., at $F = 0.275$, the second crest of the bow wave must superimpose itself almost exactly upon the stern wave behind the ship, so that an unfavorable resonance results. If in this case the center of buoyancy moves aft, the bow wave system obviously flattens out more than the stern wave rises. A detuning of the resonance may exist also, although the resonance in general does not get out of tune very much when the center of buoyancy is moved; this is shown by the fact that the humps of the curves in Figure 1 lie above one another. On the basis of these observations, it appears justifiable to assume that the aft position of the center of the buoyancy at $F = 0.275$ applies to normal ship forms.

Additional tests by Nordström with $\delta = 0.575$ yield center-of-buoyancy positions moderately far aft. These forms were varied not only with a view to minimum resistance but also to minimum propulsive power, i.e., with propeller (see solid curve). It is to be noted that the difference in the optimum position of the center of buoyancy is not great, but it is not uniquely defined. At any rate, it can be said that at normal speeds the center of buoyancy for slender ships when propelled should lie somewhat farther forward than without propulsion (to give better inflow of the water toward the propeller). Unfortunately, no propulsion tests for fuller ships have yet been undertaken.

Next, the test results were *screened* taking these findings into consideration. Several unusual forms and variations were eliminated and among the remaining ones only the normal operating speeds were considered. In Figure 4, these data have been compiled; in fact, for every form or fullness, respectively, the region is represented (cross hatched) within which the resistance does not increase more than 1 percent, i.e. immaterially, as compared with the optimum resistance. These regions may now be combined by an S-shaped curve which applies to forms with normal shoulders and minimum resistance, without propulsion. For minimum propulsive power which is determinative, of course, only one point has been determined, and that for high speeds only, and this lies approximately 0.7 percent to the right of the curve.

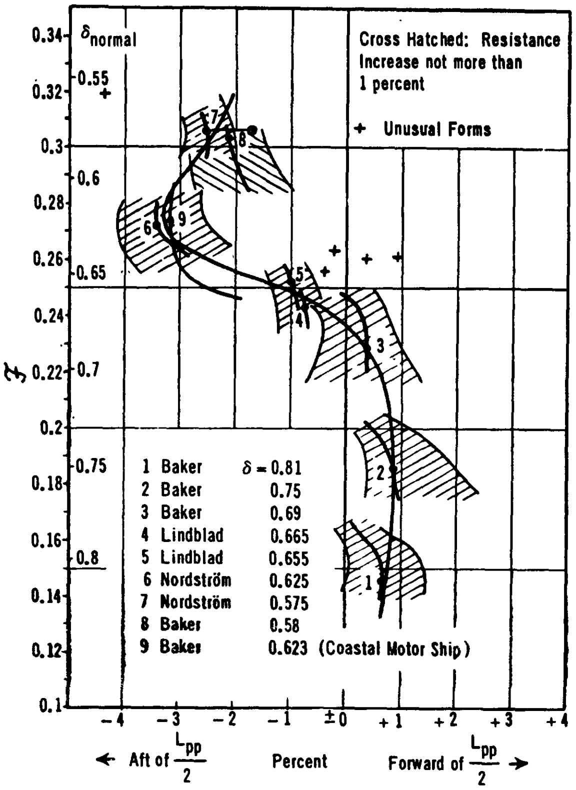

Figure 4 - Optimum Positions of the Center of Buoyancy, According to Systematic Model Tests

Some of the results of earlier evaluations, No. 10 to No. 13, which are compiled in Figure 5 deviate quite considerably from the new curve of Figure 4. The curves of Ayre and Conn have been plotted as mean values of their curves for single-screw and twin-screw vessels. For Ayre the region could also be indicated within which the resistance increases less than 1 percent as compared with that for the optimum position. At F = 0.25 to 0.3, this region is particularly large as regards the aft positions of L center of buoyancy , i.e., in the region where the second crest of the bow wave is superimposed upon the stern wave, the center of buoyancy may also lie substantially farther aft than the optimum curve indicates without any appreciable disadvantage resulting therefrom. This supports the assumption, moreover, that the center-of-buoyancy positions 6 and 9 in Figure 4 represent values for normal forms.

The curve for inland craft by Helm, curve No. 13, shows a character similar to the new curve, although the B/T values for the latter are much greater, of course. Heckscher's curve, No. 12, at $F \approx 0.2$ to 0.25 lies considerably farther aft than all the others. For minimum propulsive power, however, it comes perhaps closer to the average situation.

Generally speaking, these tests show that the optimum position of the center of buoyancy is not a real and uniquely defined form element, if a more rigorous standard is applied; rather it is largely dependent upon the details of the shape and also on the formation of the wake and suction about the propeller. The fullness of the forward shoulder appears to be particularly important, although that of the rear shoulder is important also. This may be characterized in the curve of sectional areas or in the region of the waterline by the point of the most pronounced curvature and by its distance from the end of the ship. Perhaps it is

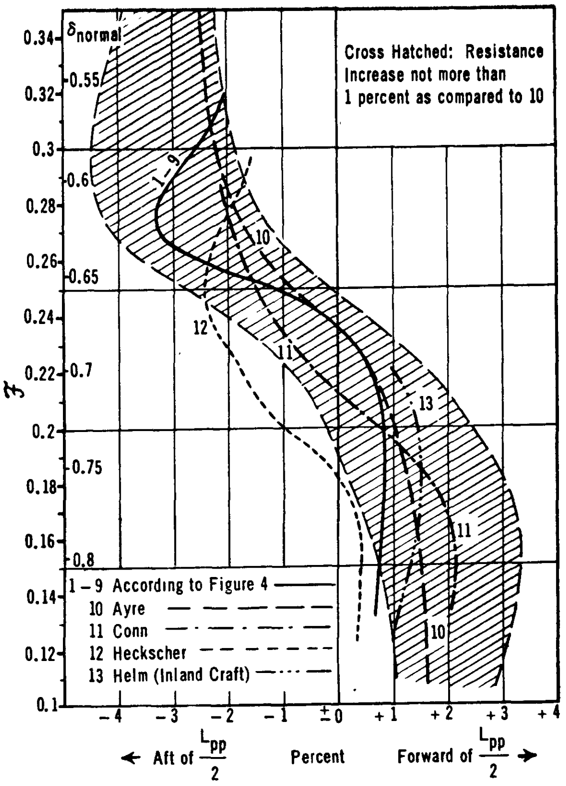

Figure 5 - Compilation of all the Evaluations of the Optimum Positions of the Center of Buoyancy

possible to set down, with the aid of the theory of wave resistance, a simple criterion for the concept of the effect of the shoulder in this matter.

Summarizing these observations, it may be emphasized that it was not the main purpose of the present compilation to add just another curve to the existing ones regarding the optimum position of the center of buoyancy. Rather on the basis of the limited data presently available in India, it was the aim of the author to point out the weaknesses of all such tests and to furnish new criteria for further research in this field.) In dealing with the position of the center of buoyancy, we are, after all, mainly concerned with a problem of the superposition of the bow wave upon the stern wave or, better yet, of the wave configurations of the entrance and of the run of the ship. To clarify this problem further, it will probably be necessary to carry out new systematic towing tests as well as additional calculations and it would be best to carry these out on an international basis. General observations in line with this train of thought will be set forth in a later article.

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