and 0.6 for both bossings and open shafts with struts.

These results are not in agreement with the geosim tests made by Allan (1950), in which there was no apparent scale effect on the bossings. There is an important difference between the two cases, however, in that the bossings used by Allan were designed to be in the flow, while those on the *Lucy Ashton* were across the flow. The resistance of the former was therefore likely to be mostly frictional, and the scale effect would be small in terms of the total resistance being measured. If the *Lucy Ashton* bossings had been aligned with the flow, their resistance might have been less than that for the shafts and struts. This difference in the bossings in the two cases makes any conclusions rather doubtful, and further research is needed to clarify the situation.

Tests carried out by the Bureau of Ships on models for four different ships showed very little difference in required power between well-designed bossings and exposed shafts and struts.

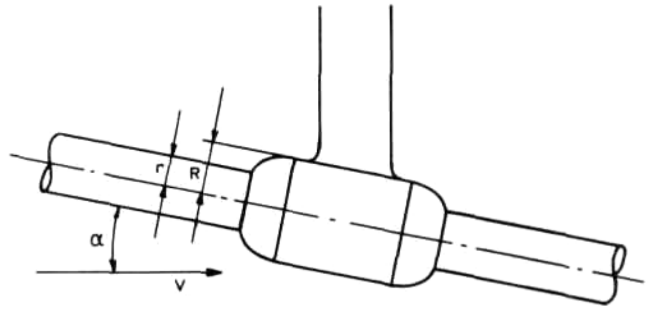
As a means of making approximate estimates of appendage resistance for design purposes, Mandel (1953) quotes overall figures derived from model tests, no reduction being made for scale effect, Table 5.

The whole question of appendage resistance is in an unsatisfactory state, both as regards making estimates of its magnitude in a given case and the application of model results to the ship. There is scope here for a great deal more research both with models and full-scale trials of ships to clarify the problem of scale effect.

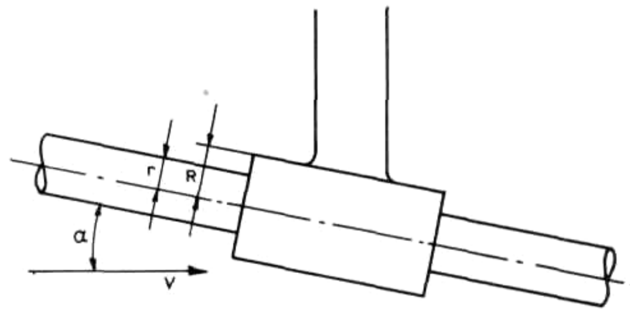
5.5 Trim Effects. Owing to the change in pressure distribution around a ship at different speeds, it will rise or sink bodily and also trim. At low speeds there is a general sinkage and a slight trim by the bow as compared with the at-rest condition (Fig. 41.) As speed increases the movement of the bow is reversed and at Fn = 0.30 or thereabouts the bow begins to rise appreciably, the stern sinks still further and the ship takes on a decided trim by the stern (Fig. 42).

As D.W. Taylor (1943) pointed out, large trim changes or sinkage of the center of gravity are symptoms rather than causes of high resistance. Nevertheless they may indicate the desirability of altering the at-rest trim by shifting the center of gravity longitudinally. The reductions of resistance which can be effected by such changes of trim as are practicable in large displacement craft are very small, but in high-speed planing craft the position of the center of gravity and the resultant still-water trim have a most important influence on performance. In both cases the possible effects can be investigated on model scale.

In the average merchant-ship form, additional trim by the stern in the at-rest condition usually results in an increase in resistance at low speeds and a decrease at high speeds. At low speeds the increased draft aft makes the stern virtually fuller, with a consequent increase in form and separation resistance, whereas



STRUT BARREL WITH FAIRED ENDS



STRUT BARREL ENDS WITH SHARP EDGES

Fig 39 Typical strut barrel ends

Table 4 —Appendage Resistance on LUCY ASHTON

Ship speed in knots	Model length in m 2.74	3.66	4.88	6.10	7.32	9.14
	Ratio $\frac{\text{increment in ship } C_r}{\text{increment in model } C_r}$ with bossings					
8	0.44	0.48	0.52	0.56	0.58	0.61
12	0.52	0.57	0.60	0.62	0.65	0.68
14½	0.10	0.12	0.14	0.16	0.17	0.20
	Ratio $\frac{\text{increment in ship } C_T}{\text{increment in model } C_T}$ with A brackets and open shafts					
8	0.48	0.52	0.56	0.58	0.61	0.67
12	0.43	0.47	0.52	0.54	0.57	0.61
14½	0.33	0.37	0.41	—	0.46	0.51

Table 5 —Approximate Resistance of Appendages

Resistance expressed as percent of bare hull resistance.

Type of ship	Value of Fn 0.21	0.30	0.48
Large, fast, 4 screws	10–16	10–16	—
Small, fast, 2 screws	20–30	17–25	10–15
Small, medium speed, 2 screws	12–30	10–23	—
Large, medium speed, 2 screws	8–14	8–14	—
All single-screw ships	2–5	2–5	—

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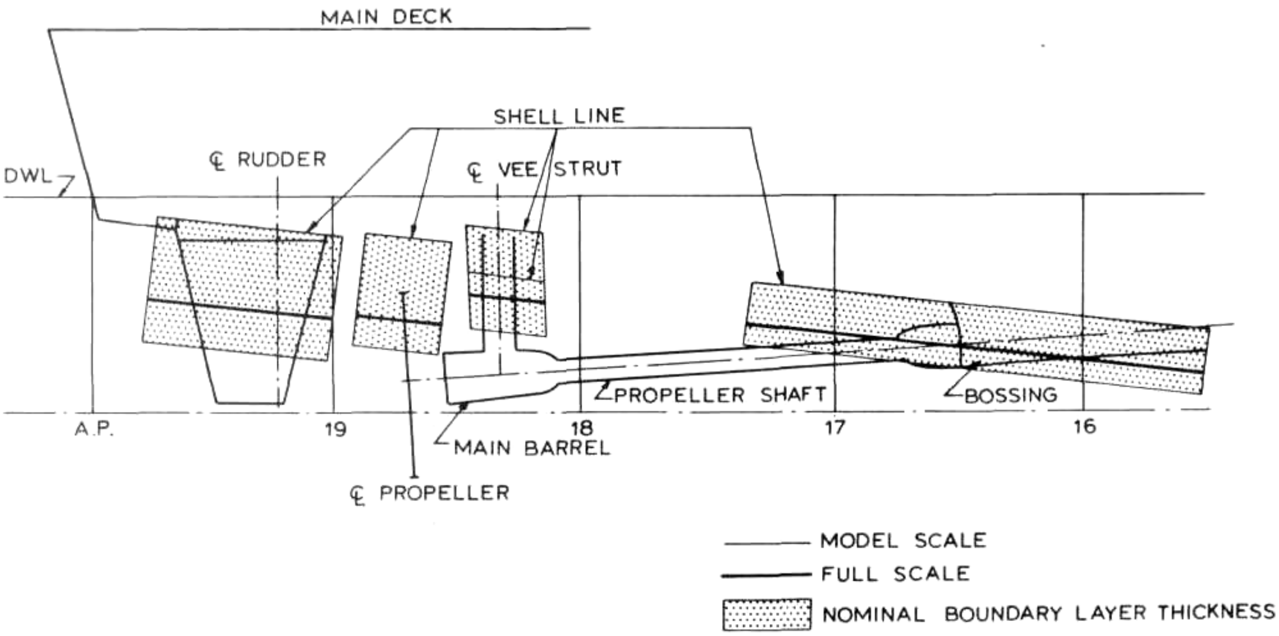

Fig 40 Nominal boundary layer thickness in way of typical appendages (Von Kerczek, et al 1983)

at high speeds this is more than offset by the reduction in wave-making due to the finer entrance in the trimmed condition.

In ballast condition, at level trim, the wetted surface per unit of displacement is much increased, so that the frictional resistance is increased also, but because of the finer form at the reduced draft, the residuary resistance is decreased. In general, except in high-speed ships, the total resistance per unit of displacement will be greater, but because of the lower displacement the total resistance and power will be reduced, and the ship in ballast will make a higher speed at the same power.

In ballast condition it is usually necessary to carry considerable trim by the stern in order to ensure adequate immersion of the propeller, and this will have similar effects to those stated in the foregoing—higher resistance at low speeds, less at high speeds. For any ship which is likely to spend an appreciable part of her time at sea in ballast condition, model experiments are usually made to investigate these effects.

5.6 Shallow-Water Effects. The resistance of a ship is quite sensitive to the effects of shallow water.

In the first place there is an appreciable change in potential flow around the hull. If the ship is considered as being at rest in a flowing stream of restricted depth, but unrestricted width, the water passing below it must speed up more than in deep water, with a consequent greater reduction in pressure and increased sinkage, trim and resistance. If in addition the water is restricted laterally, as in a river or canal, these effects are further exaggerated. The sinkage and trim in very shallow water may set an upper limit to the speed at which ships can operate without touching bottom.

A second effect is the changes in the wave pattern which occur in passing from deep to shallow water. These changes have been studied by Havelock (1908) for a point pressure impulse travelling over a free water surface.

When the water is very deep, the wave pattern consists of the transverse and diverging waves shown in Fig. 6, the pattern being contained between the straight lines making an angle a of 19 deg 28 min on each side of the line of motion of the point.

As is discussed more fully in Chapter VIII, Vol. **III,** in water of depth h the velocity of surface waves is given by the expression

$$(V_c) = (gL_W/2\pi)\tanh 2\pi h/L_W \quad (44)$$

where L_W is the length of wave from crest to crest.

As h/L_W increases, $\tanh 2\pi h/L_W$ approaches a value of unity, and for deep water this leads to the usual expression

$$(V_c)^2 = gL_W/2\pi \quad (45)$$

As the depth h decreases, and the ratio h/L_W becomes small, $\tanh 2\pi h/L_W$ approaches the value $2\pi h/L_W$, and for shallow water the wave velocity is approximately given by the equation

$$(V_c)^2 = gh \quad (46)$$

The wave pattern for the pressure point goes through a critical change when $V = \sqrt{gh}$ (see Fig. 43).

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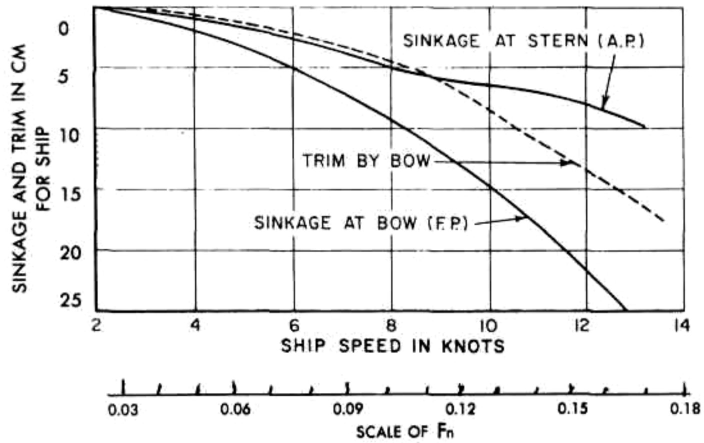


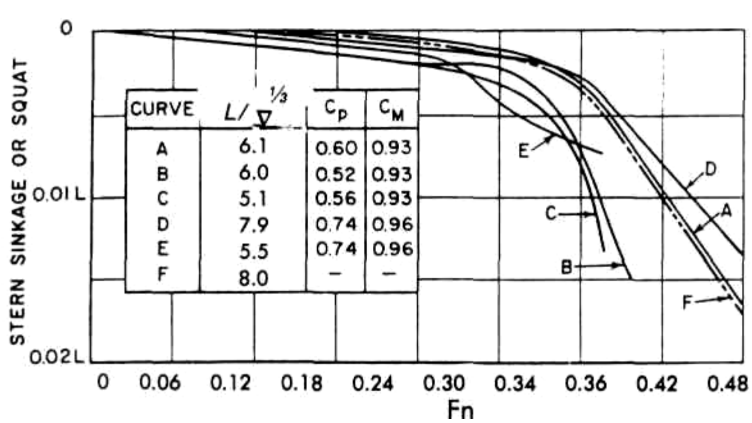
Fig 41 Changes in sinkage and trim with speed for T.2 Tanker model. Ship dimensions: 155.4 X 20.7 X 9.2 m according to Norley (1948)

For speeds less than $V = \sqrt{gh}$, the system consists of a double set of waves, transverse and diverging as in deep water, advancing with the pressure point at velocity *V*. For values of *V* less than about 0.4 $\sqrt{gh}$, the pattern is enclosed between the straight lines having an angle a = 19 deg 28 min to the centerline, as for deep water. As *V* increases above this value, the angle α increases and approaches 90 deg as *V* approaches $\sqrt{gh}$, Fig. 43.

The pressure point is now generating a disturbance which is travelling at the same speed as itself, and all the wave-making effect is concentrated in a single crest through the point and at right angles to its direction of motion. This pattern agrees with observations on models and ships when running at the critical velocity in shallow water. The whole of the energy is transmitted with the wave, and the wave is called a *wave of translation.*

When *V* exceeds $\sqrt{gh}$, α begins to decrease again, the wave system being contained between the lines given by $\sin^2\alpha = gh/(V)^2$, Fig. 43. It now consists only of diverging waves, there being no transverse waves or cusps. The two straight lines themselves are the front crests of the diverging system, and the inner crests are concave to the line of advance instead of convex as in deep water.

The effect upon resistance due to these changes in wave pattern in shallow water has been investigated by Havelock (1908) for a pressure disturbance of linear dimension *I* travelling over water of depth *h*. The resistance curves are reproduced in Fig. 44. Each curve is marked with the value of the ratio of depth of water *h* to the characteristic length of the disturbance *I*, that marked ∞ being for deep water. When the ratio *h/l* is 0.75, there is a marked peak at a speed corresponding to a value of $V/\sqrt{gl}$ = 0.86. Since $\sqrt{h/l}$ = 0.866, this corresponds to a value of unity for $V/\sqrt{gh}$, so that the peak corresponds to the speed of the wave of translation for that particular depth of water, or the critical speed. At this speed the resistance is very much greater than in deep water, but ultimately at a sufficiently high speed it becomes less than in deep water. This depth effect has an important bearing on full-scale ship trials, and can cause misleading results on



CURVE	$L/\nabla^{1/3}$	C_P	C_M
A	6.1	0.60	0.93
B	6.0	0.52	0.93
C	5.1	0.56	0.93
D	7.9	0.74	0.96
E	5.5	0.74	0.96
F	8.0	–	–

Fig 42 Curves of stern sinkage or squat in unrestricted water depth according to Miller (1963)

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