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From cargo ships to skimboards − what happens to the wave resistance hump in shallow water?

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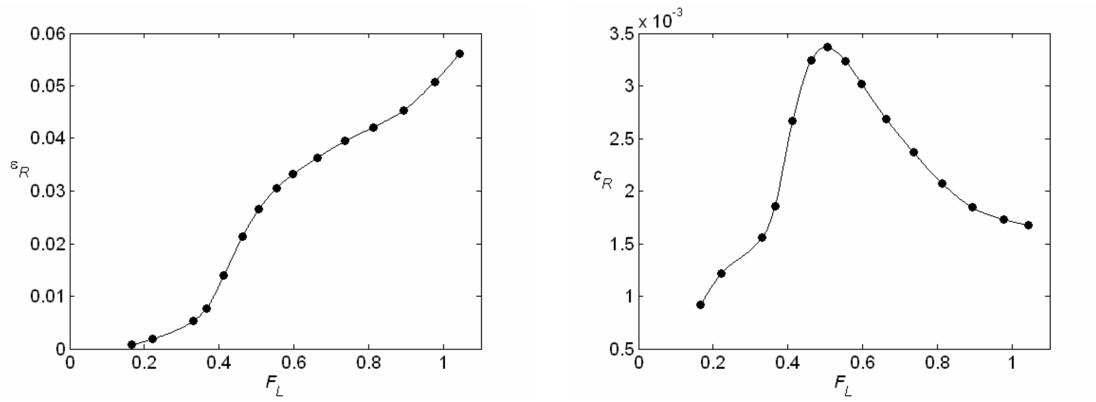
Introduction: Deep and Shallow Water

Most naval architects are aware of the wave resistance hump which occurs on surface vessels in deep water at a Froude number (based on waterline length) of around $F_n = 0.5$. "Deep water" can be considered to be a depth of 50% of the ship's waterline length or greater. The wave resistance curve has marked changes in gradient near this "hump speed", while the wave resistance coefficient has a pronounced maximum, as shown in Figure 1.



(a) (b)

Figure 1: (a) non-dimensional residuary resistance, and (b) residuary resistance coefficient, measured for a Taylor B5 hull model in deep water (from Graff et al. 1964)

In Figure 1 and throughout this article, we shall draw upon the model test results of Graff et al. (1964), which remain one of the defining sets of experimental wave resistance results in varying water depth. These tests were undertaken in the Duisburg towing tank in Germany. This towing tank has a width of 10.1 m, sufficient to minimise blockage effects near $F_{nh} = 1.0$ for the 3 m model size used. Results in narrower tanks are invariably subject to blockage effects near $F_{nh} = 1.0$, causing production of forward-propagating solitons over a wide range of speeds, and markedly different results to what would be experienced in open water (Chen 1999). The full length of the tank was also needed to minimise starting transients.

The hull referred to here is a Taylor standard series model B5, which is a transom-stern destroyer-type hull, the lines plan of which is given in Graff et al. (1964). Tests were done up to and above $F_n = 1.0$, although speeds above $F_n = 0.6$ would be unrealistic for a destroyer in practice. The residuary resistance was defined as the total measured resistance, minus the estimated frictional resistance (based on the Schoenherr formulation, van Manen and van Oossanen 1988). Attempts to calculate a form factor showed that this was very small for these hulls and, due to the measurement uncertainty, a form factor was not included. The residuary resistance coefficient is assumed equal to the full-scale value at the same Froude number, and consists essentially of wave-making resistance.

As well as the deep-water "hump speed", another, more severe, wave resistance hump occurs in very shallow water. "Very shallow water" can be taken to be 15% of the ship's waterline length or less. Figure 2 shows the residuary resistance for a Taylor B5 hull in very shallow water.

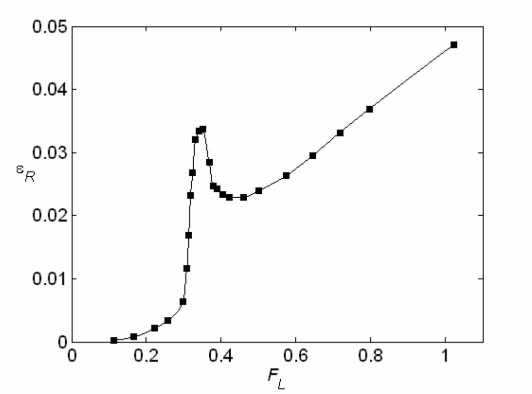


Figure 2: Measured residuary resistance for a Taylor B5 standard series destroyer hull model at *h*/*L* = 0.125 (from Graff et al. 1964)

We see that the wave resistance has a well-defined peak at a lower speed than the deep-water hump speed. This peak occurs at a speed that depends on the water depth, rather than the ship length, i.e. at a depth-based Froude number $F_{nh} = 1.0$.

Nomenclature

C_R	residuary resistance coefficient, = $R_R / \left(\frac{1}{2}\rho U^2 S\right)$
F_{nh}	depth-based Froude number, = $U / \sqrt{gh}$
F_n	length-based Froude number, = $U / \sqrt{gL}$
g	acceleration due to gravity, = 9.81m/s^2
h	water depth (m)
L	ship waterline length (m)
R_R	residuary resistance (N)
S	wetted surface area (m^2)
U	ship speed through water (m/s)
W	ship weight (N)
ρ	water density (kg/m^3)

Wave Resistance in Intermediate Water Depths

We shall now look at the problem of intermediate water depth (i.e. not "very shallow" and not "deep"). Figure 3 shows the residuary resistance of the Taylor B5 hull in a range of water depths, from deep to very shallow.

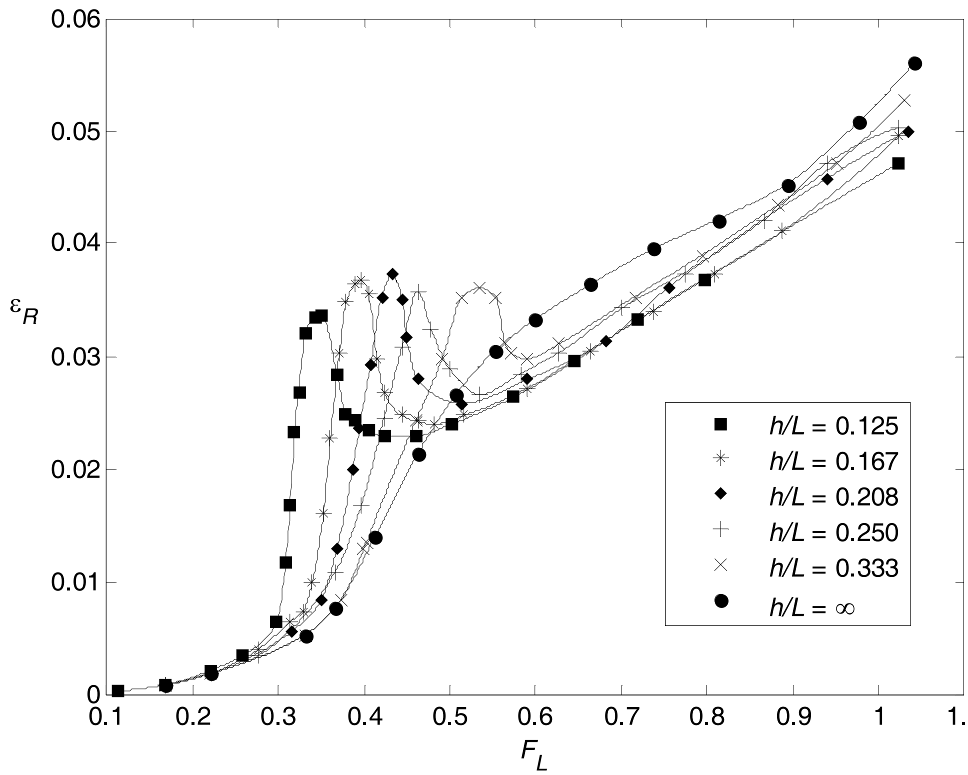


Figure 3: Residuary resistance measured for a Taylor B5 hull model in different water depths (from Graff et al. 1964)

We see that, as the depth decreases below half the waterline length, the "hump" which occurs in deep water at $F_n = 0.5$ becomes a defined local "peak" which occurs at a lower and lower speed as the depth decreases. Also of note is the decreased wave resistance at high speeds, as compared to the deep-water value. Since the frictional resistance is assumed independent of water depth, the total resistance is also smaller in finite water depth than in deep water at high speeds. This fact is commonly observed for high-speed displacement ships which can pass through the shallow-water resistance hump, as they are able to achieve higher top speeds in shallow water than in deep water.

We can consider the finite-depth wave resistance as the deep-water wave resistance, plus a finite-depth correction. This finite-depth correction is shown in Figure 4.

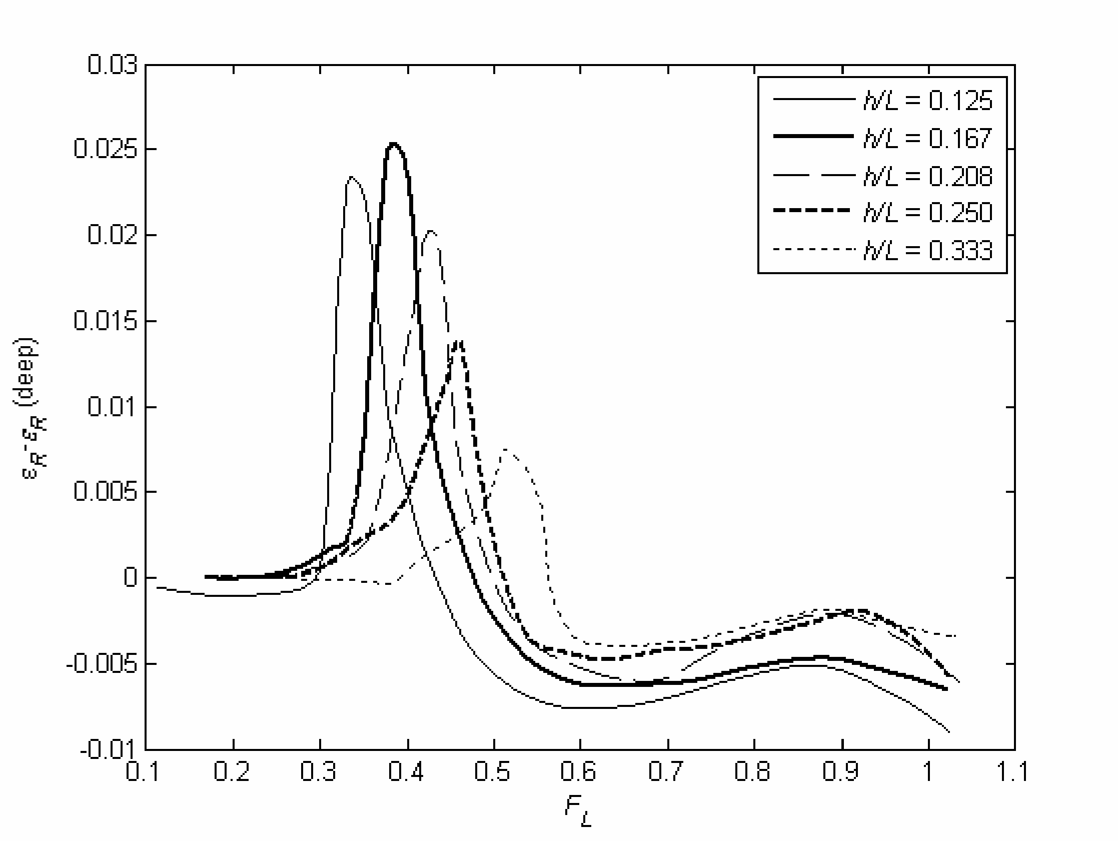


Figure 4: Residuary resistance increase over deep-water values, measured for a Taylor B5 hull model in different water depths (from Graff et al. 1964)

The finite-depth correction has a peak at a speed which depends on the water depth. In fact, if we plot against F_{nh} as in Figure 5 we see that in each case the peak occurs at approximately the shallow-water critical speed $F_{nh} = 1.0$.

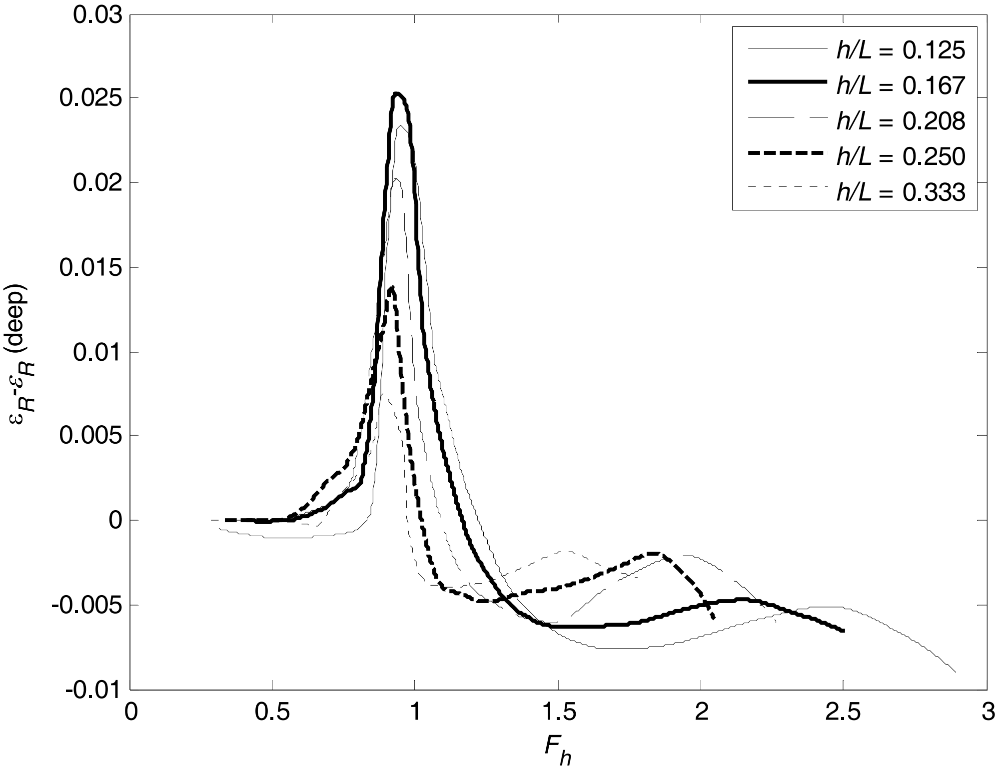


Figure 5: Residuary resistance increase over deep-water values, measured for a Taylor B5 hull model in different water depths (from Graff et al. 1964)

Note that the magnitude of the shallow-water wave resistance peak tends to increase as the depth decreases. This fact is borne out in slender-body flow field calculations (Tuck and Taylor 1970, Tuck et al. 2000, Gourlay and Tuck 2001), which show that the finite-depth correction dominates the deep water wave resistance near $F_{nh} = 1.0$ in shallow water.

Frictional Resistance

The residuary resistance quoted in Graff et al. (1964) is found by subtracting the Schoenherr frictional resistance estimate (which is independent of water depth) from the total resistance. In practice, the frictional resistance will change as the water depth changes. At speeds below $F_{nh} = 1.0$, decreasing the water depth has the effect of increasing the local flow velocities past the hull, and hence increasing the frictional resistance (Schlichting 1934, Harvald 1983).

Therefore the breakdown of measured resistance into frictional and residuary cannot be expected to be accurate when using a depth-independent formulation such as the Schoenherr method. However the advantage of having done this in the Graff et al. (1964) experiments is that the effect of water depth on total resistance can be easily inferred from the residuary resistance values given.

Other Hull Types

The preceding discussion centres on experimental results for a destroyer-type hull, which is a high-speed displacement vessel. For large cargo ships, the wave resistance curve would also look similar to Figure 3. However these ships typically cannot reach the deep-water hump speed of $F_n = 0.5$, so would never pass the finite-depth wave resistance peak. The effect of shallow water for them is simply to steepen the wave resistance curve at a lower speed, and hence decrease their top speed accordingly. The speed loss that occurs on entering shallow water is well understood by cargo ship captains.

For planing vessels, hydrodynamic lift is minimal below $F_n = 0.5$, so the shallow-water effects described for displacement vessels will apply equally to planing vessels in this range. At higher planing speeds, the wave resistance and total resistance are less in shallow water than in deep water (Toro 1969).

Extreme Shallow Water

Watching a skimboard being ridden in 1−2 cm of water is an excellent demonstration of the high lift and low drag which accompanies planing vessels at very shallow depths. Towing a child on a boogie board at water depths down to 1−2 cm also demonstrates this effect clearly.

The extreme shallow water problem is analogous to that of a wing in ground effect: the skimboard glides in the same way that a seabird glides close to the ocean surface. Comparisons can also be drawn with the large loads supported by industrial bearings at small clearances, according to lubrication theory. Tuck and Dixon (1989) developed a simplified extreme-shallow-water planing theory, which showed that only very small angles of attack, and hence small drag coefficients, are required to give large lift. Only minimal waves and hence minimal wave resistance are produced in this case.

For sailing speed records, the World Sailing Speed Record Council has recognized the potential advantages of extremely shallow water, requiring a minimum depth of 10 cm, or half the waterline beam, for a valid record attempt. The location of the current speed record, Lüderitz Canal, has not taken full advantage of this rule, instead keeping the depth at 1m for safety in the event of crashes.

Conclusions

- In deep water (water depth greater than half the shiplength), surface vessels have a small change of gradient (“hump”) in the wave resistance curve at a Froude *length* number of 0.5.
- In very shallow water (water depth less than 15% of the shiplength), surface vessels have a large local maximum in the wave resistance curve at a Froude *depth* number of 1.0.
- In intermediate water depths, the wave resistance curve is a combination of the deep-water curve and a finite-depth correction. This correction has a local maximum at a Froude *depth* number of 1.0, and becomes increasingly important as the water depth decreases.
- For vessels which can pass through the shallow-water wave resistance peak, the high-speed wave resistance in shallow water is less than in deep water.

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