Viscous resistance and wave resistance

Objectives

After working through these notes you should be able to:

1. describe the boundary layer characteristics affecting resistance
2. distinguish between a friction line and a correlation line
3. explain and determine the position of humps and hollows in the wavemaking resistance curve.

References:

Clayton, B. R. and Bishop, R. E. D. (1982) *Mechanics of marine vehicles,* Spon, London. Chapter 5.

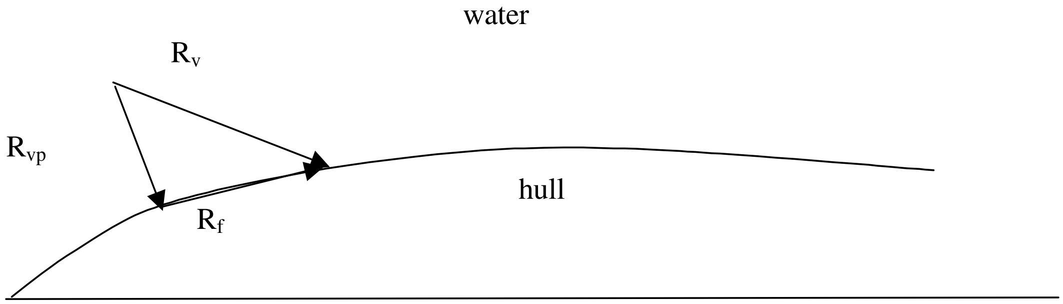
Gutelle P.(1984) *The design of sailing yachts*. Macmillan, London

Lewis E. (Ed.) (1988) *Principles of Naval Architecture* Vol 2. Society of Naval Architects and Marine Engineers, New York. Chapter 5

Tuck, E.O., Scullen, D.C. and Lazauskas, L. (2001) "Ship-wave patterns in the spirit of Michell", IUTAM Symposium on Free-Surface Flows, Birmingham, July 2000. Proc. ed. A.C. King and Y.D. Shikhmurzaev, Fluid Mechanics and its Applications Volume 62, Kluwer Academic Publishers, Dordrecht, 2001, pp. 311--318

1 Viscous resistance

Viscosity results in the water exerting a force on the underwater part of the hull. Consider an element of the hull surface in more detail:

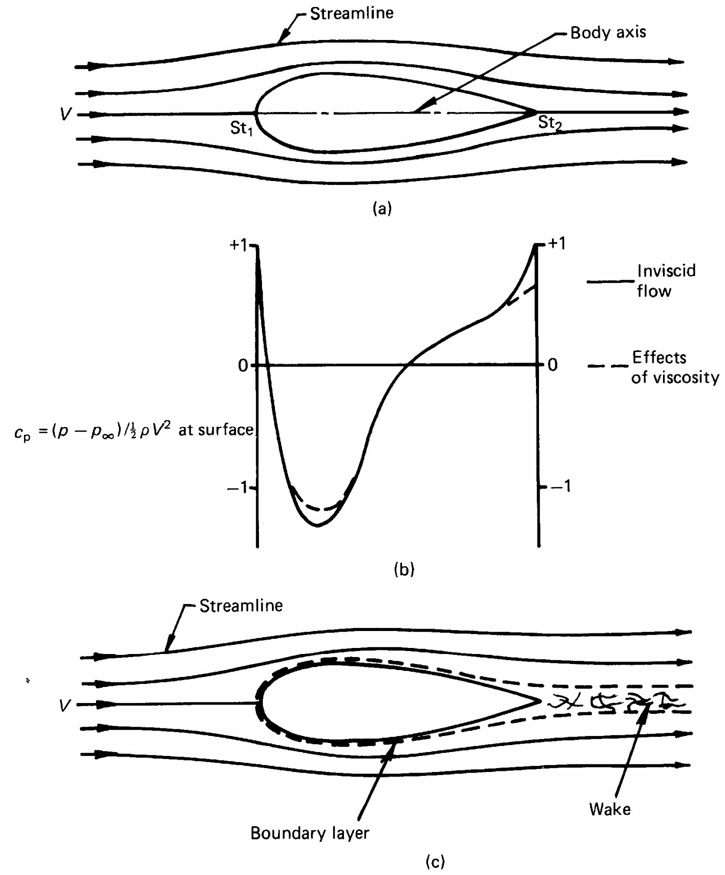


We can divide the viscous resistance into components perpendicular and parallel to the hull surface. The sum of the parallel components is the frictional resistance F_{ro} and the sum of the perpendicular components is the viscous pressure resistance R_{vp}, also called the pressure form resistance, eddymaking resistance or separation resistance.

2 Viscous pressure resistance R_{vp}

It is easiest to consider viscous resistance by ignoring the water surface and assuming the object in the water is full submerged i.e. no wave effects. When water flows past the hull it exerts a pressure on the hull. (this is a consequence of Bernoulli's equation. If the fluid were perfect (i.e. inviscid) then the sum of the pressures integrated over the hull would be zero. However, the presence of the boundary layer results in a decrease in these pressures over the stern, leading to a net resistance. This is the viscous resistance.

The pressures around the stern of the ship depend on the local curvature of the hull, which may cause the boundary layer to separate away from the hull, generating eddies.

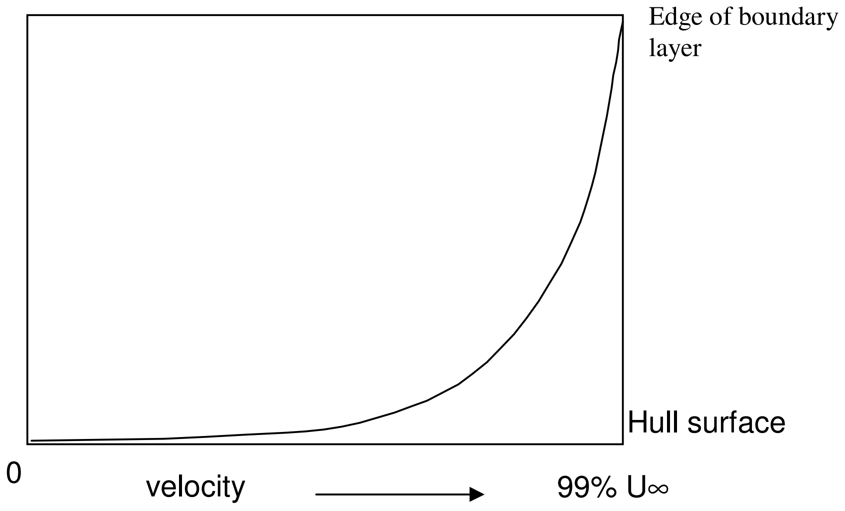


Clayton & Bishop (1982)

3 Skin Friction Resistance:

Skin friction resistance is the component of resistance obtained by integrating the tangential forces over the hull surface. It is independent of the form of the body and of the free surface.

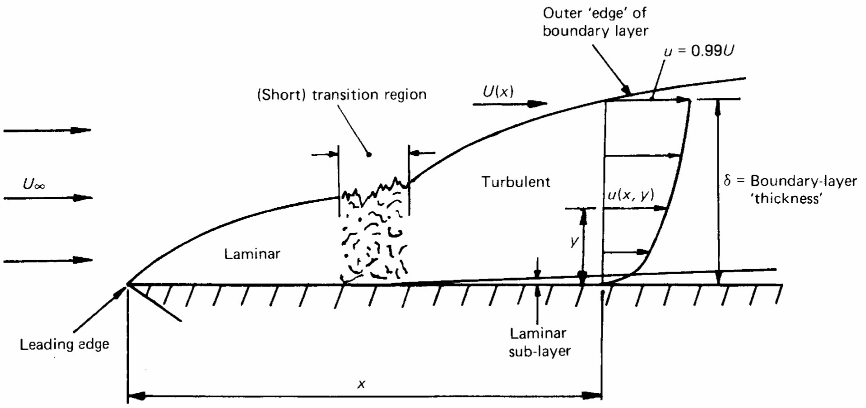
When water flows past a boundary, as shown in the figure, the water nearest the boundary tends to stick to it and will therefore have zero velocity.



With increasing distance from the surface the velocity approaches that of the free stream U_∞ asymptotically and there is no sharp dividing line between the boundary layer and the rest of the flow. The boundary layer is thus defined as the region of fluid where there is a velocity gradient. The boundary layer thickness is the distance from the surface to the point at which the speed becomes 99% of the maximum flow speed.
It is the total force between all slipping layers of fluid in the boundary layer that gives rise to the skin friction resistance.

4 Laminar & Turbulent Flow:

Consider the flow along one side of a thin, smooth plate parallel to the direction of flow. In the real fluid a velocity gradient arises entirely due to the viscous action near the surface.



Clayton & Bishop (1982)

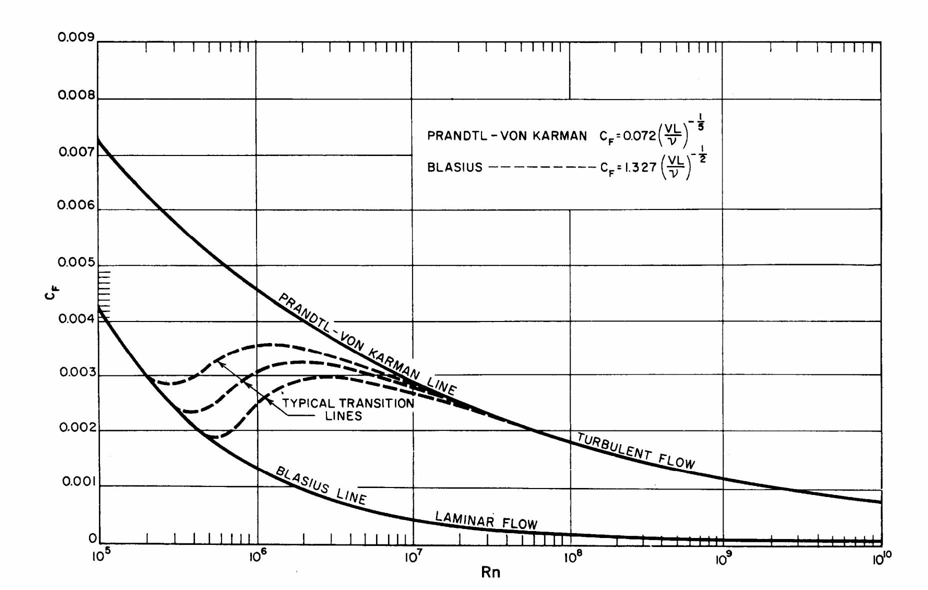
The boundary layer begins at the leading edge of the plate. As more fluid is slowed down, so the thickness of the layer increases. Within this 'young' boundary layer the flow is in regular layers, or laminar flow, with no turbulence. As it thickens, the laminar layer becomes unstable and the motion is disturbed. Irregularities of flow develop into turbulence and the boundary suddenly thickens to absorb this turbulence. The boundary layer thus undergoes transition to turbulent flow. The turbulent boundary layer is much thicker and results in higher sheer stresses, hence greater frictional resistance.

The short region where the boundary layer flow changes from laminar to turbulent is called the transition region. The point along the surface at which transition occurs depends on factors such as surface roughness and turbulence in the free stream flow.

However it was Sir Osborne Reynolds in the 1880's who showed that above a critical value of the ratio vL/ν flow becomes turbulent and behaves in a completely different manner. This ratio is known as Reynolds number (Re or Rn).

$$\mathrm{Re} = \frac{\mathrm{vL}}{\nu}$$

Generally, boundary layers are laminar up to $R_e < 10^5$.
The Re at which transition occurs is called the critical Reynolds number.
Whether the flow is laminar or turbulent has a significant effect on the skin friction resistance, as can be seen from the diagram below. It should also be noted that as the size is reduced (say from full scale ship to model) the velocity must increase to maintain the same Reynolds number. Obviously this would be hard to achieve in a ship model experiment.



(Lewis 1988)

5 Laminar sublayer:

Downstream of transition the flow is almost entirely turbulent, but the turbulent motions must die out close to the surface (they cannot pass through the surface). Hence a very thin laminar sublayer is formed beneath the turbulent boundary layer. A body is said to be hydraulically smooth if the surface irregularities do not protrude through the sublayer.
The sublayer thickness is given by:

$$\delta_l = \frac{12\nu \mathrm{Re}^{\frac{1}{4}}}{u_\infty}$$

only about 0.2mm (200 microns) for a typical 100m ship.

6 Effect of hull roughness on frictional resistance

If the hull is not hydraulically smooth, the roughness that protrudes beyond the sub-layer into the main boundary layer will increase the frictional resistance. A typical roughness height for a ship hull is 230 microns, ranging from 172 to 400 The change in friction resistance due to a change in roughness height is given in Townsin (Transactions RINA, 1980) as:

$$\Delta R_F = 0.058\left[(h_1)^{\frac{1}{3}} - (h_2)^{\frac{1}{3}}\right]$$

where
ΔR_F = fractional change in frictional resistance
h_1, h_2 = roughness heights in microns of the two different surfaces.

Implicit in this formula is a minimum threshold of h equal to the sub layer thickness.
So if a ship has a sublayer thickness of 200 microns and a paint roughness of 250 microns, the increase in friction is 0.026, or 2.6%
The underwater area of the hull of a ship is painted with an antifouling paint, which contains toxins to prevent marine growth (weed) attaching to it. Most ships are now painted with self-polishing paints which gradually erode over a year or two, thus maintaining a reasonably smooth finishes and very little marine growth. However, if the paint system fails, or runs out of toxins, then marine organisms such as weed or barnacles will attach to the hull causing a large increase in roughness, hence frictional resistance. A barnacle is about 5000 microns high, so frictional increases can easily reach 50% if the paint system is not well maintained.

7 Skin Friction Resistance Formulations:

Froude postulated that the total resistance of any hull, either ship or model, is the sum of two components; frictional resistance and residuary resistance:

$$R_T = R_F + R_R$$

He measured the resistance of thin planks, from 0.6m to 15.2m in length and since they were thin and had chamfered ends, he assumed that their resistance was due to friction only. He derived a formula for the frictional resistance of a plank of arbitrary length and surface area at a specified speed.

Froude's formula for the frictional resistance of a plank is:

$$R_F = fSV^n$$

where f is a numerical constant, S is the wetted surface area and V the speed. This formula has been replaced by a modern equivalent.

Accurate estimation of frictional resistance is vital in order to determine the total resistance of a full scale craft.
A skin friction resistance coefficient C_F can be defined:

$$C_F = \frac{R_F}{0.5\rho v^2 S}$$

Since Froude's early work a large number of investigators have conducted experimental studies with the aim of obtaining friction lines. These can be used to determine the skin friction resistance at a given Reynolds number:

Schoenherr $\frac{0.242}{\sqrt{C_f}} = \log_{10}(R_n \times C_f)$

Hughes $C_f = \frac{0.066}{(\log_{10} Rn - 2.03)^2}$

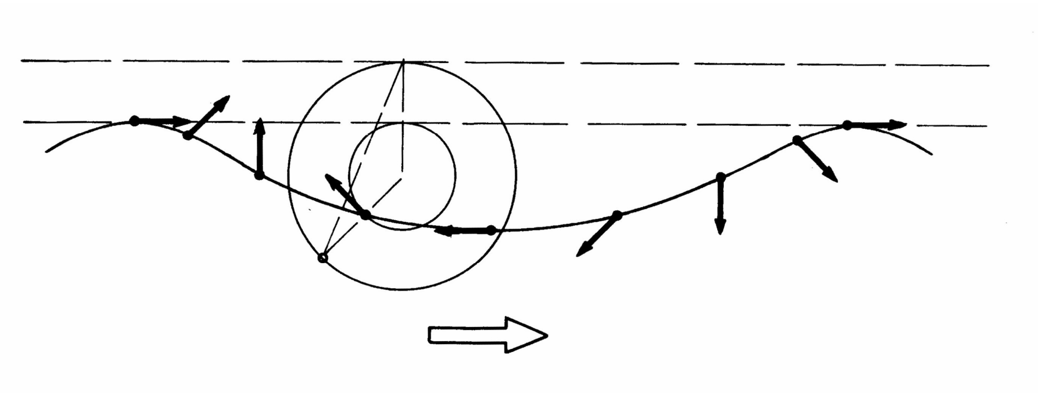
ITTC 1957 $C_f = \frac{0.075}{(\log_{10} Rn - 2)^2}$

Of these, only the Schoenherr line is a true friction line. The Hughes and ITTC formulae are not really friction lines, they just give a value for the friction coefficient that yields the correct answer for total resistance when scaling model test results to full scale. i.e. they include a fudge factor, which is called a correlation factor. So these formulae are called correlation line formulae, to indicate they do not just calculate friction, they include other scaling effects as well.

8 Wavemaking Resistance:

The wavemaking resistance is associated with the energy involved with generating the pattern of waves seen when a vessel travels along the surface.
Prior to looking at the wave pattern created by a moving vessel we should take note of three properties of gravity waves.

i) Water particles do not move with the wave, instead they travel in circular orbits as shown in the figure. These orbits decay with depth (orbital motion is negligible at depths greater than half the wave length).



Gutelle (1984)

ii) In deep water the speed of the wave is a function of the wave length:

$$C = \sqrt{\frac{g\lambda}{2\pi}}$$

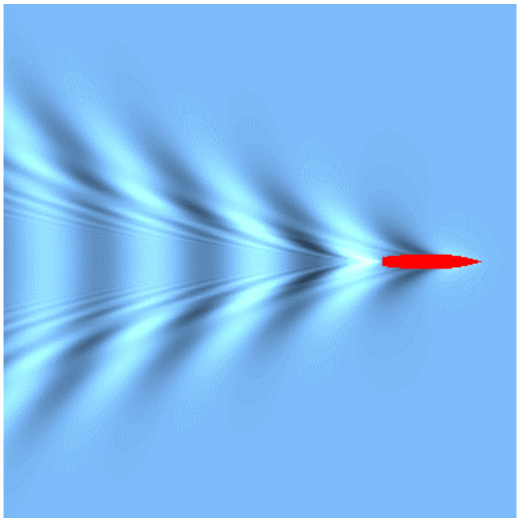
where
λ = wave length
C = wave phase velocity

This means that longer waves travel faster than shorter ones.

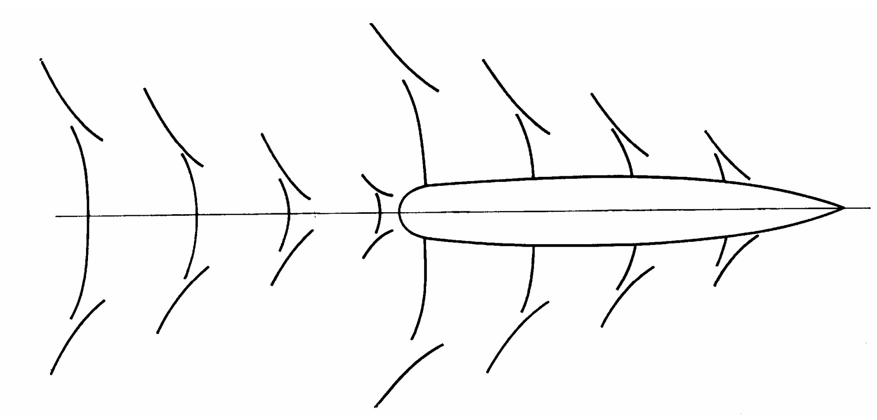
iii) The energy in a wave system is proportional to the wave height squared. Thus, if a vessel creates large amplitude waves its wavemaking resistance will be very high.

9 The wave system

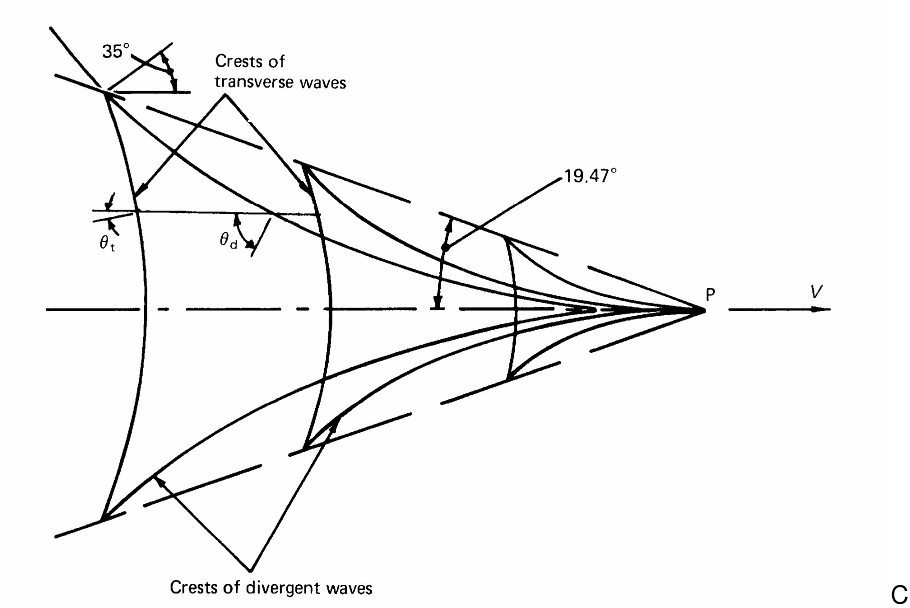
In about 1900 Lord Kelvin considered a single pressure point travelling in a straight line over the surface of the water, sending out waves which combine to form a characteristic pattern of transverse and diverging waves.



Tuck et al (2001)



Lewis (1988)



Clayton & Bishop (1982)

The whole pattern of waves is contained within two straight lines starting from the point and making angles of 19 deg 28 min on each side of the longitudinal axis. The distance between each transverse wave depends on the speed.

The wave pattern generated by a vessel can be considered to be made up of a number of Kelvin systems. In front of the ship there is a high pressure area and therefore a noticeable bow wave is formed as a part of the transverse and diverging wave system. Also at the shoulders of the hull and at the stern, wave systems are formed.

The main wave systems are caused by the bow and the stern. Both bow and stern divergent systems are visible aft of the ship, however, the two transverse systems interact and generally only the resultant is visible. Depending on the phasing of these systems the crests may coincide, with increased wave amplitudes, greater energy content, hence higher resistance. However, a crest from the bow may coincide with a trough from the stern system, giving a lower resultant wave height, less energy content and lower resistance. Much research has been devoted to theoretical methods of calculating wavemaking resistance and to their experimental verification. However the calculation of resistance cannot yet be done with sufficient accuracy to replace model experiments, but they are valuable guides.

10 The wave resistance curve – humps and hollows