The Physics of Sailing

"There is nothing-absolutely nothing-half so much worth doing as simply messing about in boats."

River Rat to Mole, in "The Wind in the Willows," by Kenneth Graham

America's Cup 2003, February 16, Race 2. Team New Zealand against Alinghi. Alinghi uses the staysail.

Outline

- ***Hulls***
- ***Keels***
- ***Sails***

Hulls

- *"Hull Speed"*
- *Resistance*
- *Shape*
- *Stability*

Hull Speed

- *Hull speed is determined by the length of the boat.*

- *Water waves are dispersive, i.e., their speeds depend on the wavelength of the wave; long wavelengths are faster.*

- *Boats generate a wave at the bow. The speed of this wave must equal the speed of the boat.*

Hull Speed

- *At first, the bow waves generated have short length; several waves are seen along the side of the boat.*
- *As the boat moves faster, the wavelength increases, until it equals the length of the boat.*
- *When the wavelength becomes longer than the boat, the stern begins to fall into the trough of the wave and the boat is ploughing "uphill" on the bow wave.*
- *The resistance increases dramatically.*

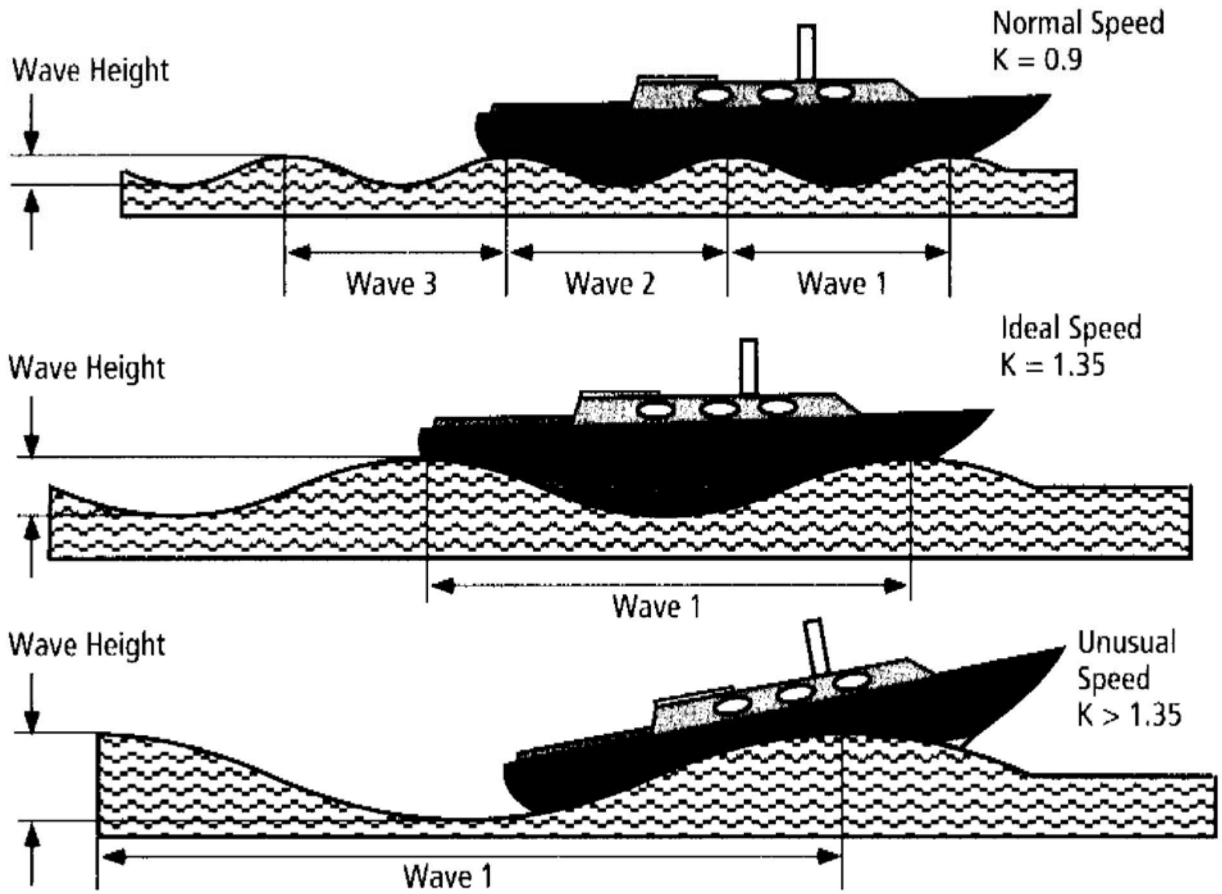
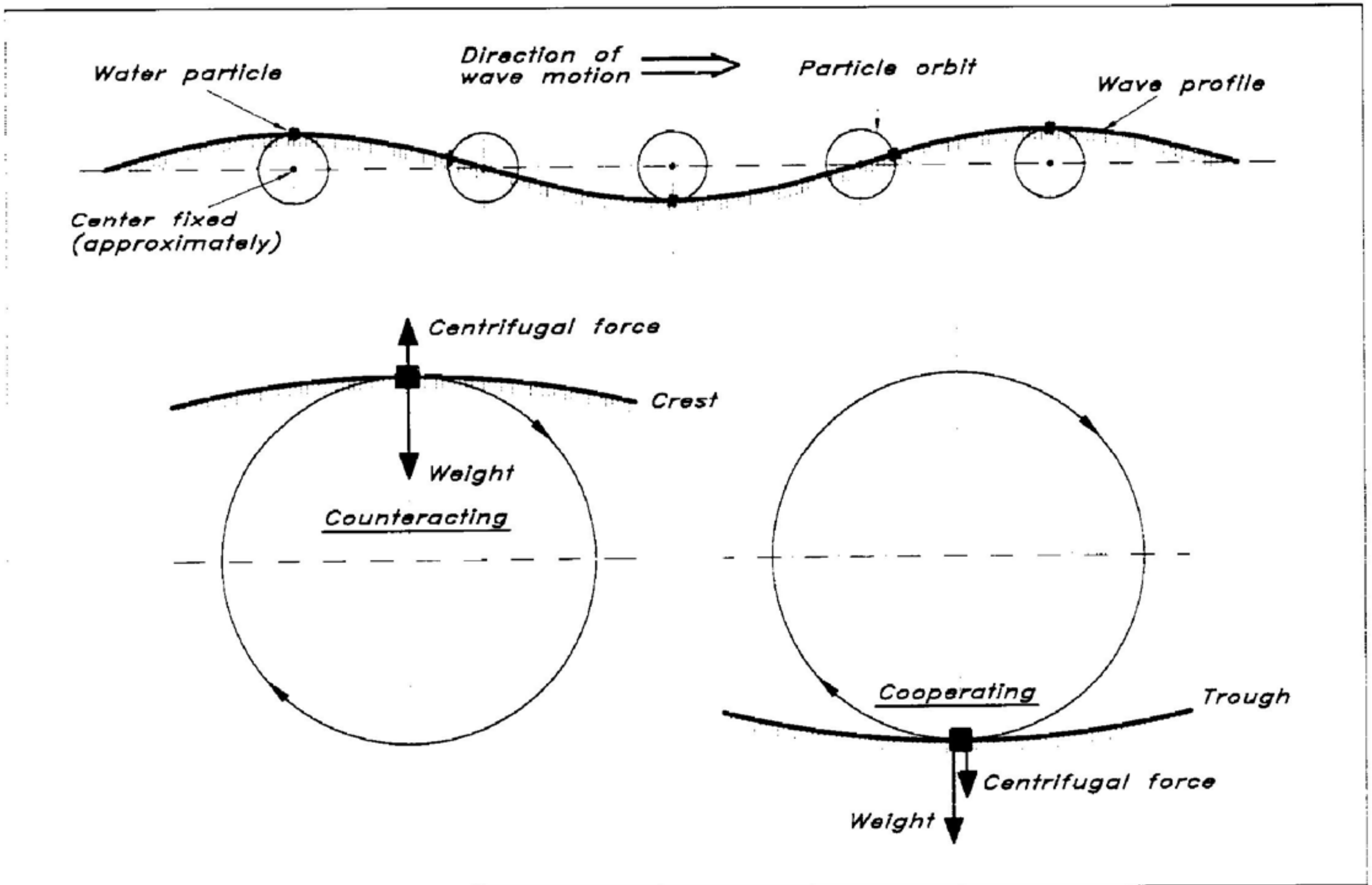
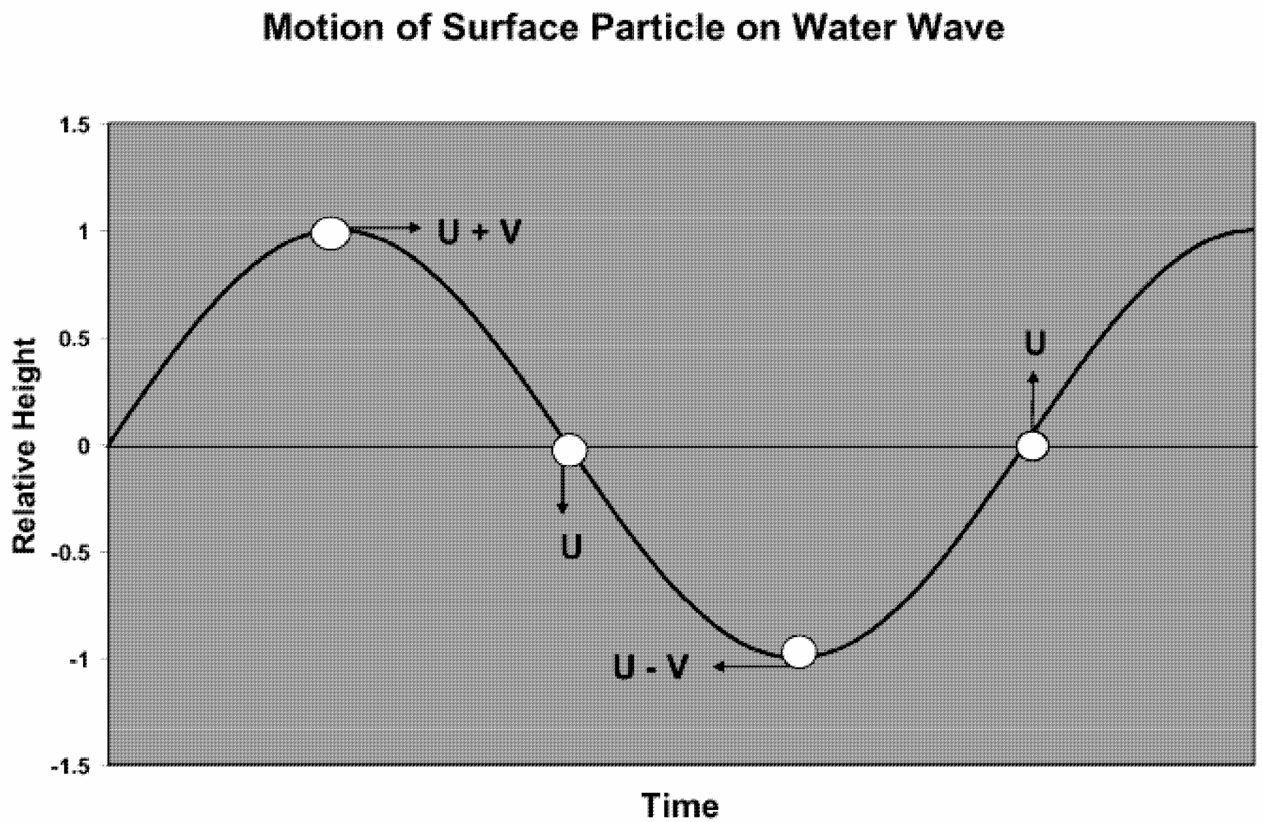


Figure 7.5 *Bow Wave and Boat Speed*


721
721
TX 1922



Water particle
Direction of wave motion
Particle orbit
Wave profile
Center fixed (approximately)
Centrifugal force
Crest
Weight
Counteracting
Cooperating
Trough
Centrifugal force
Weight


Motion of Surface Particle on Water Wave
1.5
1
0.5
0
-0.5
-1
-1.5
Relative Height
U + V
U
U - V
U
Time

HULL SPEED FORMULA

Change in Potential Energy = Change in Kinetic Energy

$$mgh = mg(2A) = \frac{m}{2}\left[(v+u)^2 - (v-u)^2\right]$$
$$= 2mvu$$

which yields

$$gA = vu \quad . \qquad (1)$$

Now we need a relationship between v and u. We can obtain this by noting that a wave can be described by a sine function.

$$y = A\sin(\frac{2\pi x}{\lambda})$$ *, where* λ *= wavelength of wave.*

Near the origin, where x is small,

$$y = A\sin(\frac{2\pi x}{\lambda}) \approx A(\frac{2\pi x}{\lambda})$$

and the ratio of y to x is then:

$$\frac{y}{x} = A\frac{2\pi}{\lambda} \quad . \qquad (2)$$

Now the ratio of the vertical to horizontal displacements near the origin is the same as the ratio of the vertical to horizontal velocities, u/v. Hence, we have

$$\frac{u}{v} = \frac{y}{x} = A\frac{2\pi}{\lambda} \quad .$$

Since u and v are each constant, we can use this relationship to substitute for u in (1). This yields

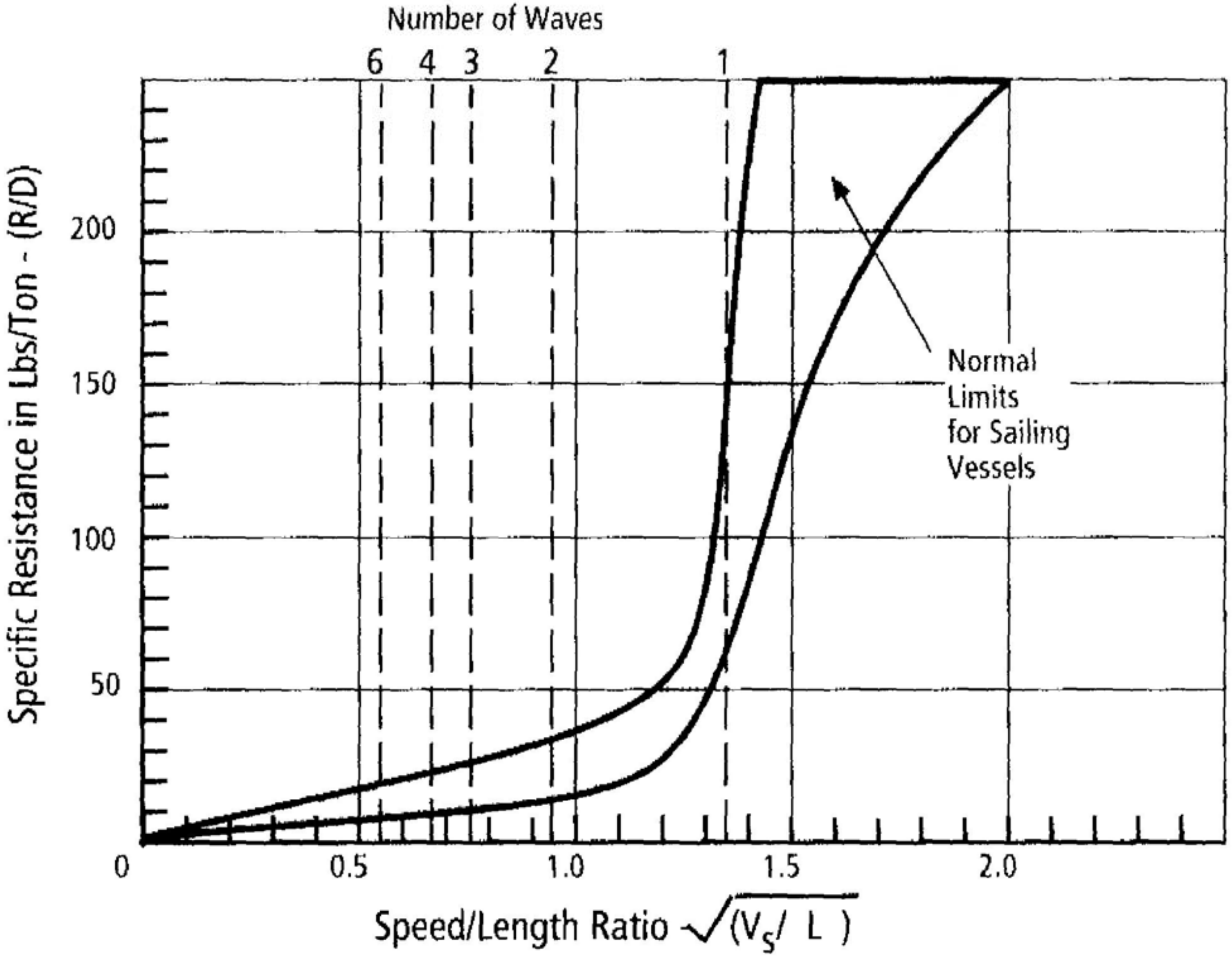
$$gA = A\frac{2\pi}{\lambda}v^2 \quad ,$$ *and solving for v,*

$$v = \sqrt{\frac{g\lambda}{2\pi}} = \sqrt{\frac{g}{2\pi}}\,\sqrt{\lambda} = 1.34\sqrt{\lambda(ft)}$$ *(v in knots).*

Table 1.1 Wave/Hull Speeds

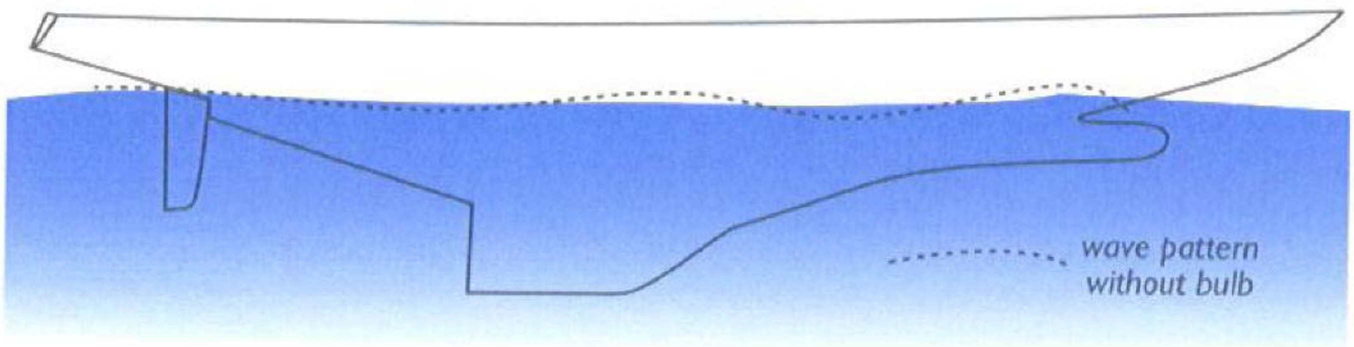
Wavelength (feet)	Speed (ft/sec)	Speed (Mph)	Speed (Knots)
1	2.3	1.6	1.4
5	5.0	3.4	3.0
10	7.1	4.8	4.2
20	10.1	6.9	6.0
30	12.4	8.5	7.4
50	16.0	10.0	9.5
75	19.5	13.3	11.6
100	22.6	15.4	13.4
200	31.9	21.8	18.9
300	39.1	26.7	23.2

PLATE 43.—*Waves produced by a stone thrown into a pond. The waves of short wavelength travel more slowly than the long waves. Therefore, the short waves are to be found on the inside of the circle with the long ones on the outside.*



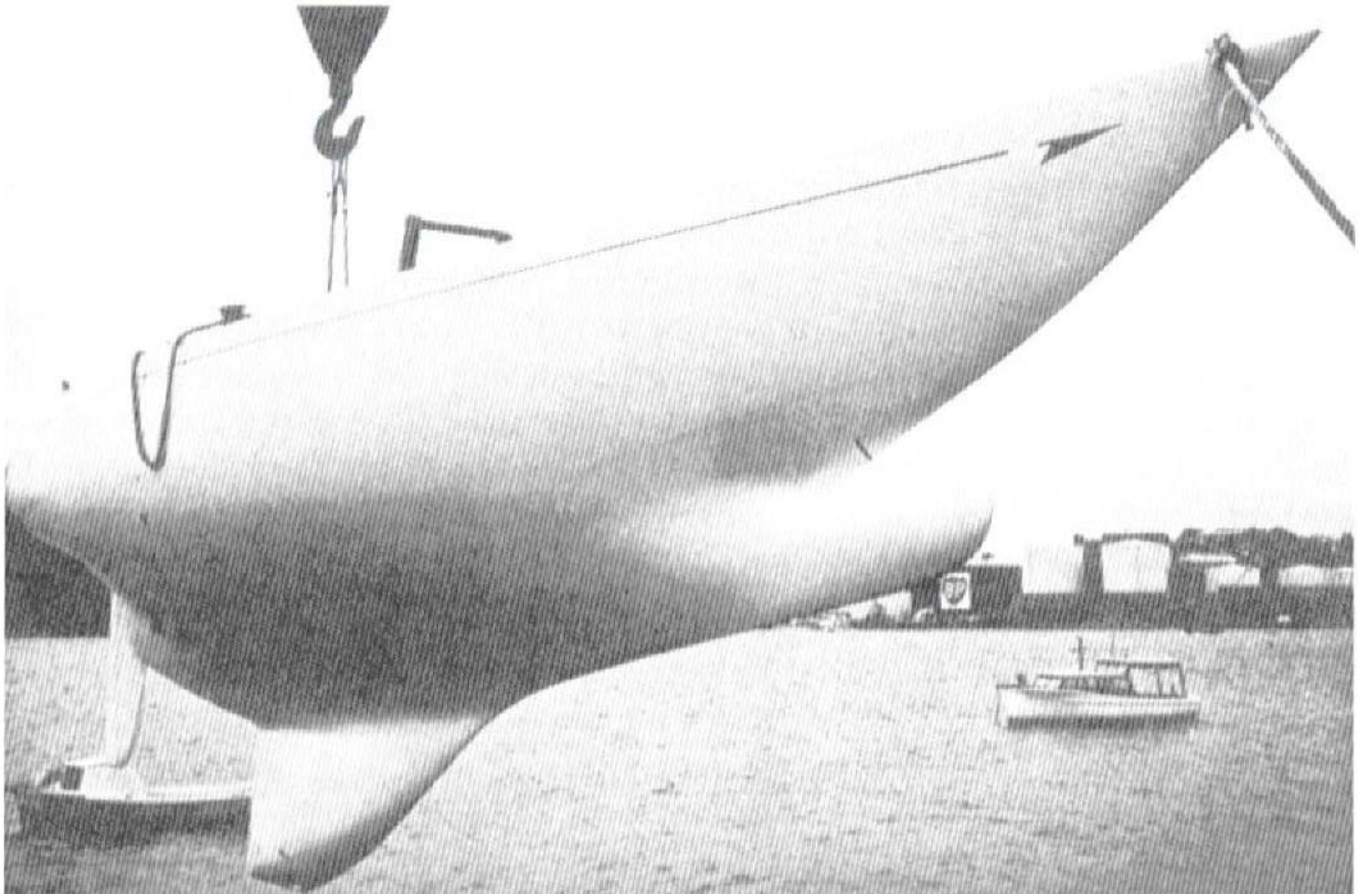
Number of Waves
6
4
3
2
1
200
150
100
50
0
0.5
1.0
1.5
2.0
Specific Resistance in Lbs/Ton - (R/D)
Speed/Length Ratio $\sqrt{(V_S/\ L\ )}$
Normal Limits for Sailing Vessels

FIG. 1.8
Bulbous bows



The bulbous bow—a tubular extension of the hull just below the waterline—has both intrigued and frustrated sailors. The bow extension reduces drag by creating its own bow wave ahead of the hull's bow wave, and the two wave patterns cancel each other out. These extensions are commonplace on large ships, which use them to realize savings in wavemaking drag of 5 to 15 percent. (The wave reduction shown in the above illustration of an 8-Meter equipped with a bow extension is based on actual data from tank-testing bulbous-bow ships.) Cargo ships use them to burn less fuel, and racing sailors would love to use them to go much faster. But pitching effects and the inability to fine-tune a bulb's wave-reducing benefit to a particular hull speed (which is essential to their success in ship applications), among other problems, have rendered them experimental curiosities in yacht design.

Photo 2.6 An example of an unsuccessful attempt to improve the speed potential of a 6-Metre boat by means of a bulbous bow. Since then others have tried to apply the same idea to sailing craft.



HULL RESISTANCE

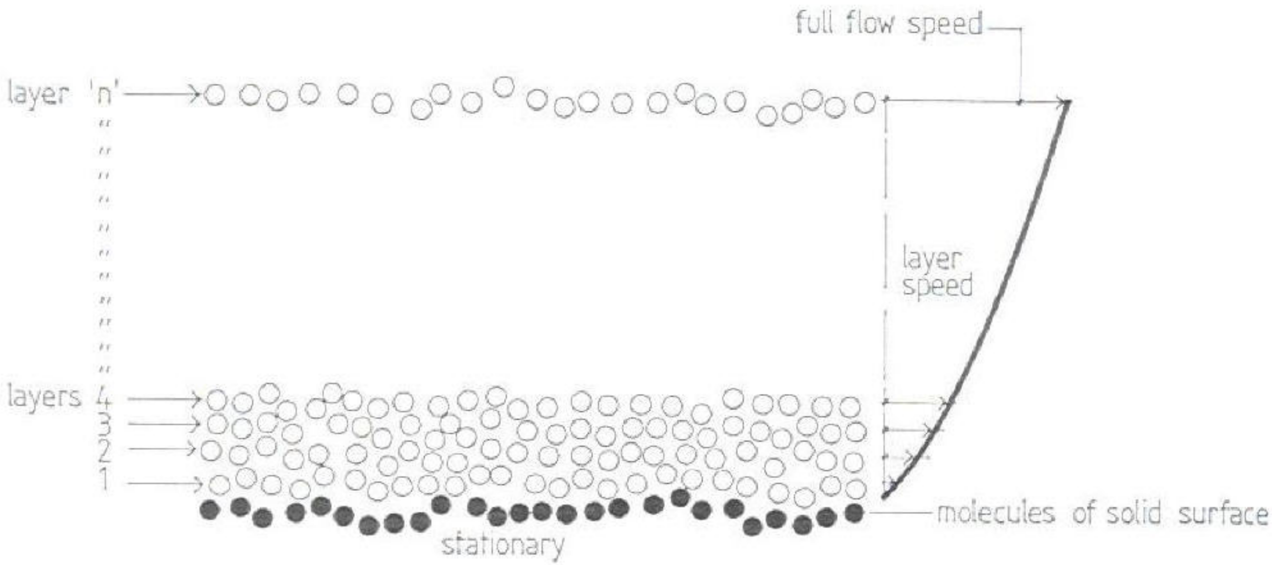
- *Surface Resistance*

  Shearing
- *Turbulence*

  Reynolds No.
- *Eddies*

  Separation
- *Shape*

Friction: Intermolecular forces



REYNOLDS NUMBER AND TURBULENCE

$$R = \frac{Lv}{\mu / \rho}$$

L = length *v = velocity*

μ = viscosity *ρ = density*

Viscosity is a measure of the force necessary to shear a fluid:

$$\tau = \mu\left(\frac{\Delta v}{\Delta y}\right)$$

τ = stress (force/area)

y = direction perpendicular to flow

The Reynolds number is the ratio of inertial forces (vρ) to viscous forces (μ/L). Reynolds observed that laminar flow becomes turbulent for $R \approx 10^6$.

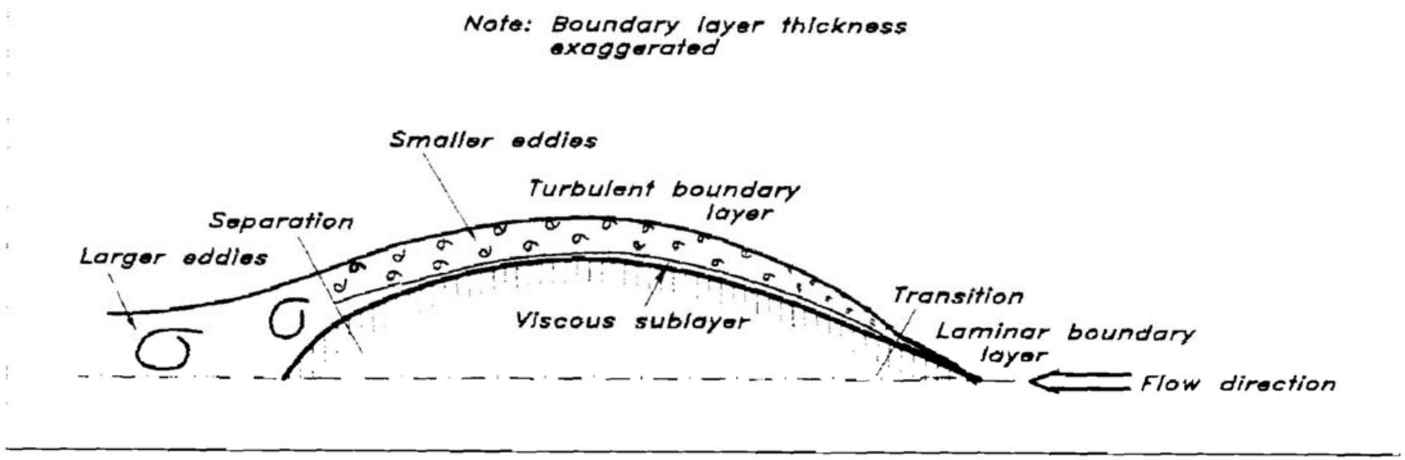
For water:

$\mu = 1.0 \times 10^{-3}$ $N \cdot sec/m^2$ and $\rho = 10^3$ kg/m^3 , which yields

$$R = L\,v \times 10^6 \quad .$$

So that turbulence will begin when $L\,v \sim 1$.

5 knots = 2.5 m/sec = v, so L v = 1, when L = 0.4 m !


Note: Boundary layer thickness exaggerated
Smaller eddies
Turbulent boundary layer
Separation
Larger eddies
Transition
Viscous sublayer
Laminar boundary layer
Flow direction

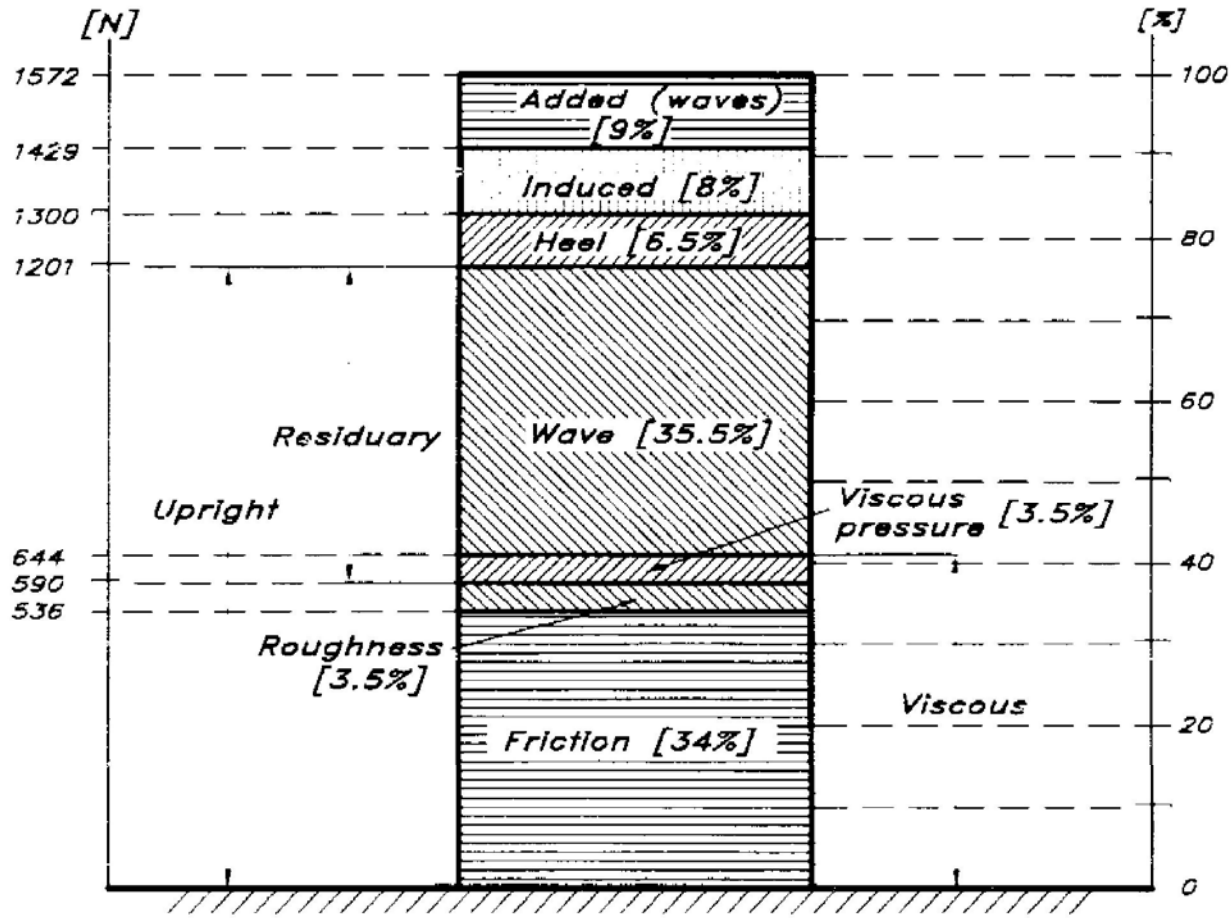
Roughness

- *Hull should be "smooth".*

  Bumps will introduce turbulence sooner and/or will produce larger turbulence.

- *"Polishing" does not help very much.*

  Shearing must take place!

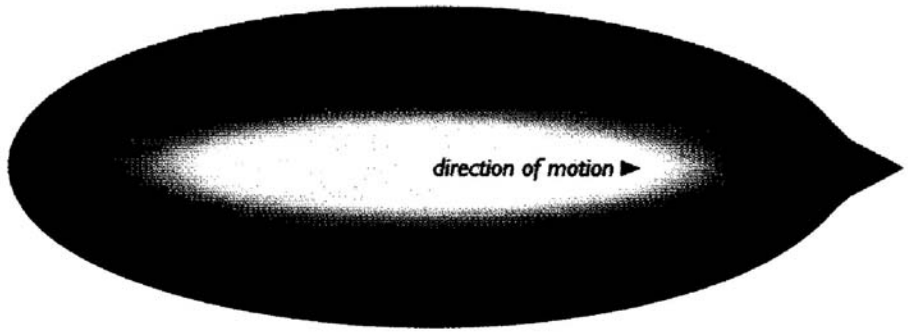


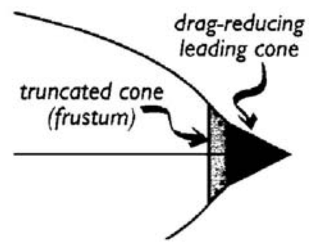
Resistance components, YD–40 beating to windward at 6.8 knots [F_n = 0.35]

Hull Shape

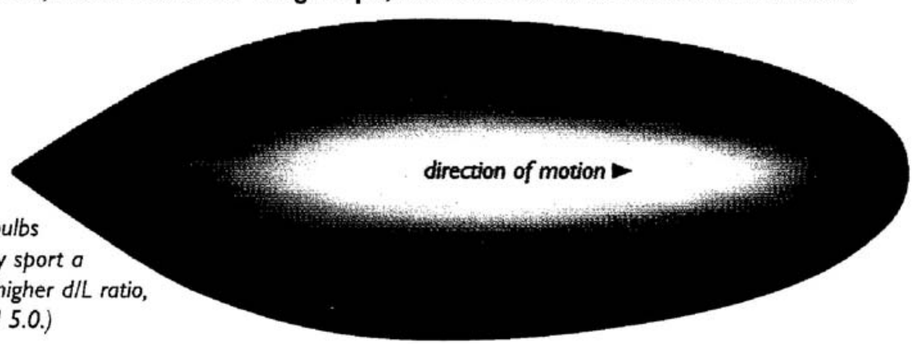
- *Hull shape determines how fast a boat can accelerate and how fast it can go in “light’ winds.*
- *Generally speaking, narrower, shallower hulls are faster, but less stable and hold less “cargo”.*
- *Exact shape for fastest hull is still a subject of debate.*

FIG. 1.1
Newton's solid of least resistance





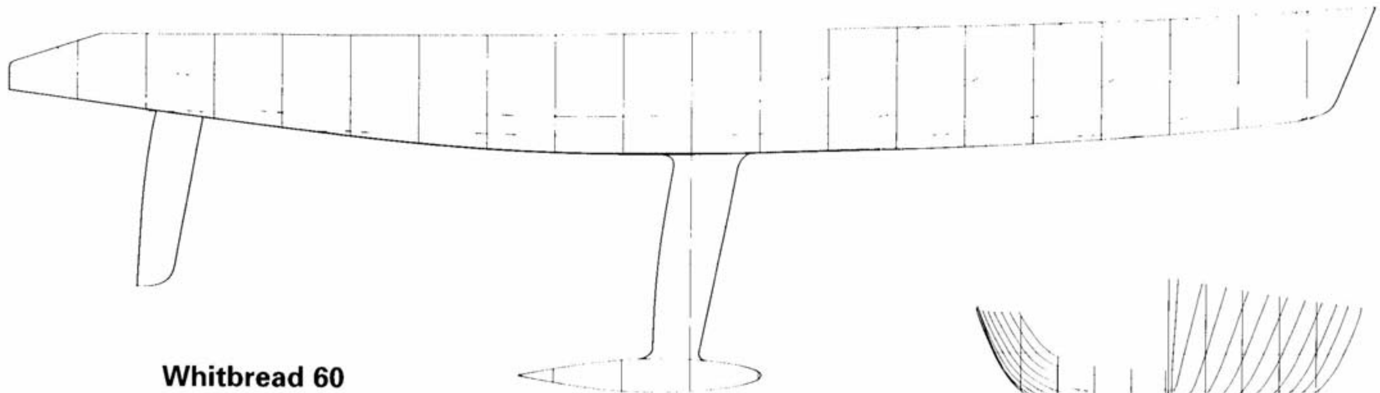
In his *Principia* of 1687, Sir Isaac Newton provided a mathematical blueprint for creating a shape he called the *solid of least resistance*. An ellipse with a circular cross section was capped by a *frustum* (a flat-topped cone), which was in turn capped by a cone. The diameter/length (d/L) ratio of the body could vary; we have shown it above at 2.75. Newton believed such a form would produce the least amount of drag when moving point-first through water. Wrote Newton: "This proposition I conceive may be of use in the building of ships." His "proposition" became a focal point of ship design research, but the idea of a perfect form ultimately proved imperfect. Current research into submerged objects like keel bulbs has produced a far different, blunt-nosed low-drag shape, as shown below at the same d/L ratio.

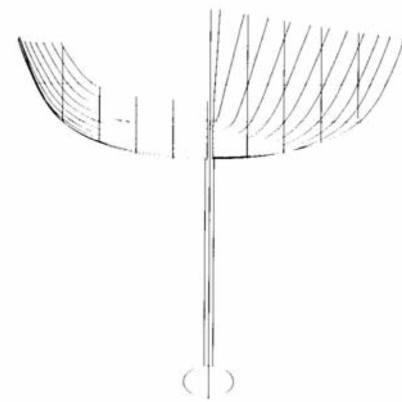


(Keel bulbs actually sport a much higher d/L ratio, around 5.0.)

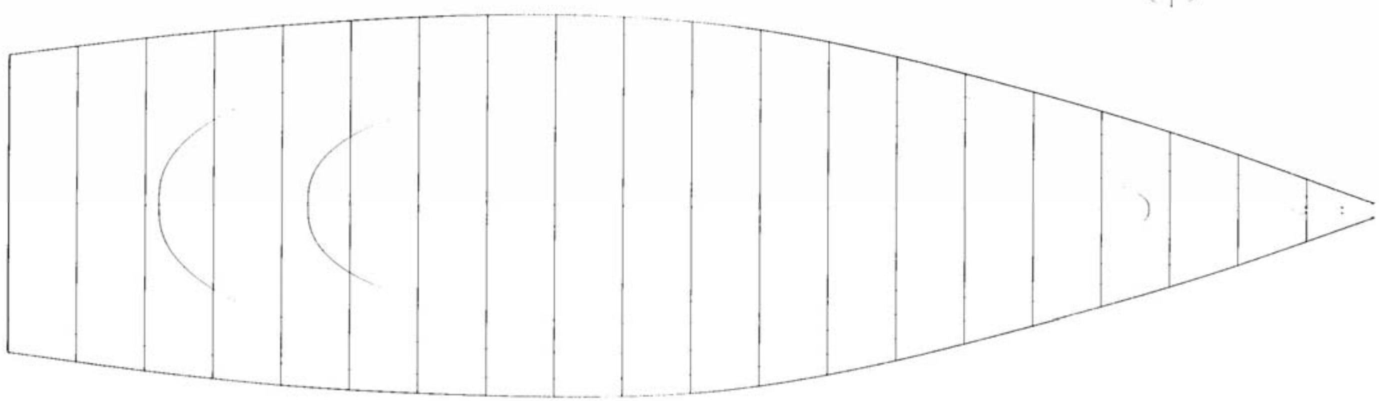
Modern Racing Hull Design

- *Narrow, sleek bow*
- *Shallow, flat bottom toward stern*
- *Square stern, normally above water line*
- *Able to plane under certain conditions*





Whitbread 60
LOA: 60' 7"
LWL: 51' 0"
Beam max: 17' 2"
BWL: 13' 3"
Draft: 12' 3"
Displ: 30,000 lbs
Prismatic coefficient: 0.540




illbruck

Keels

- *Keels are necessary to provide resistance against “side-slipping”, and to provide counter balance for sideways force of wind on sails.*

- *A large keel adds a lot of surface resistance.*

- *Want a balance between positive keel action and negative keel resistance.*

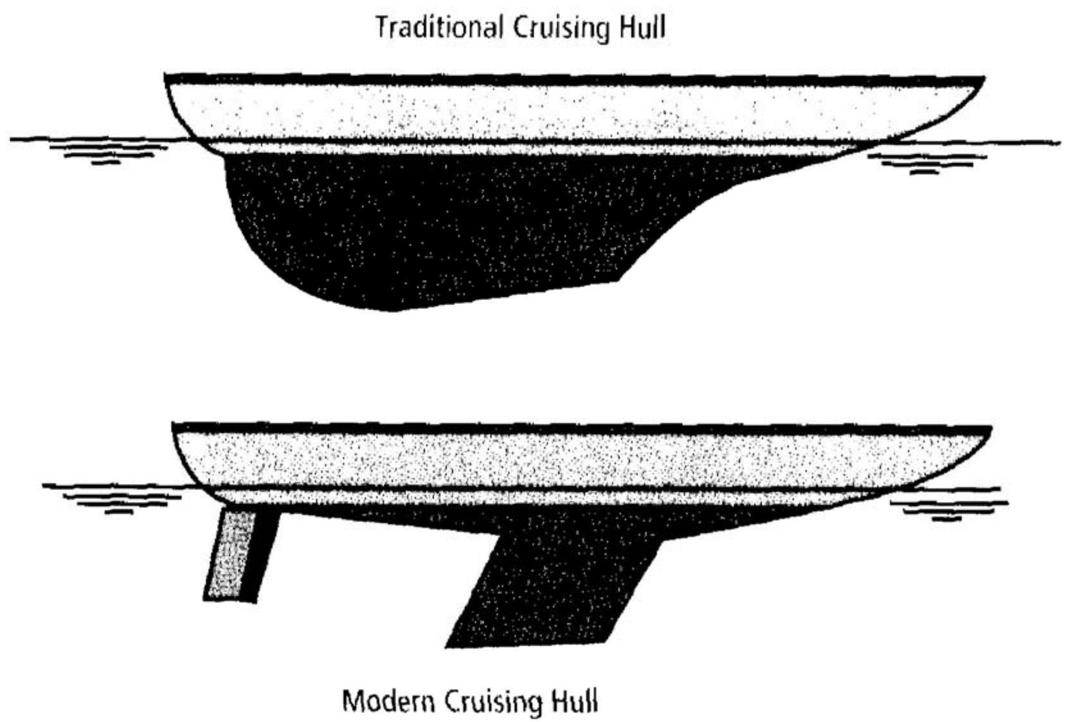


Figure 7.12 Typical Lateral Sections

Wing theory

- *Keels and sails act like airplane wings; i.e., they can provide “lift”.*

- *Proper design helps a lot!*

Lift (Bernoulli's Principle)

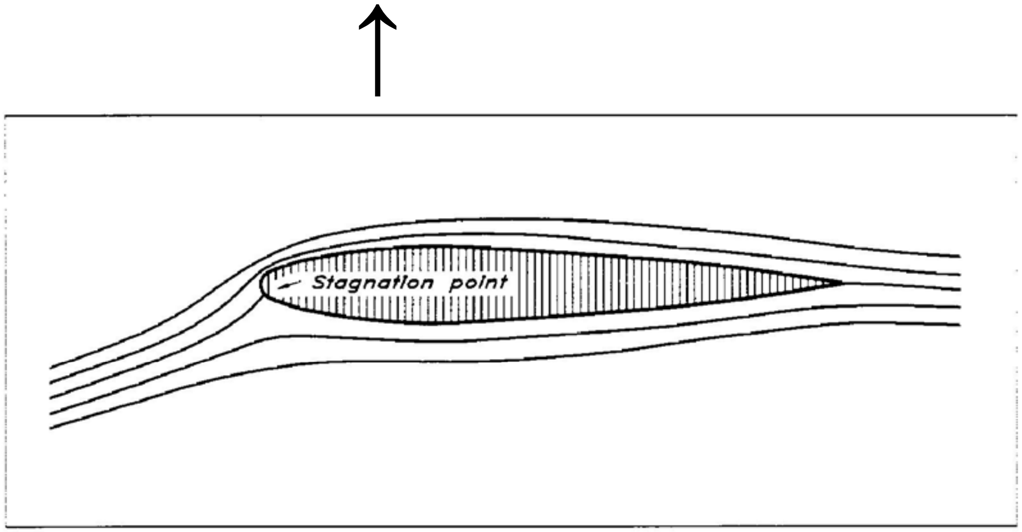
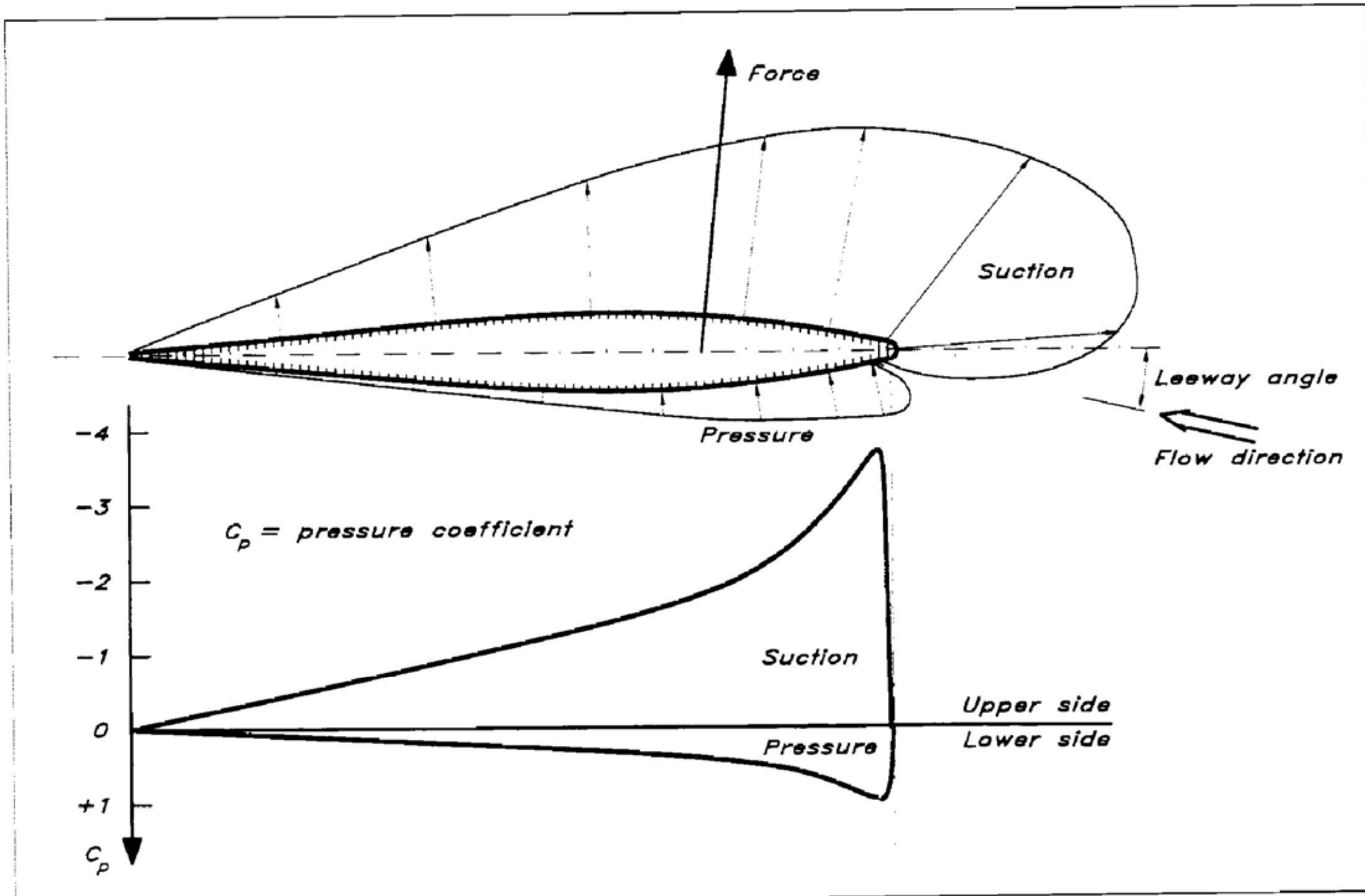
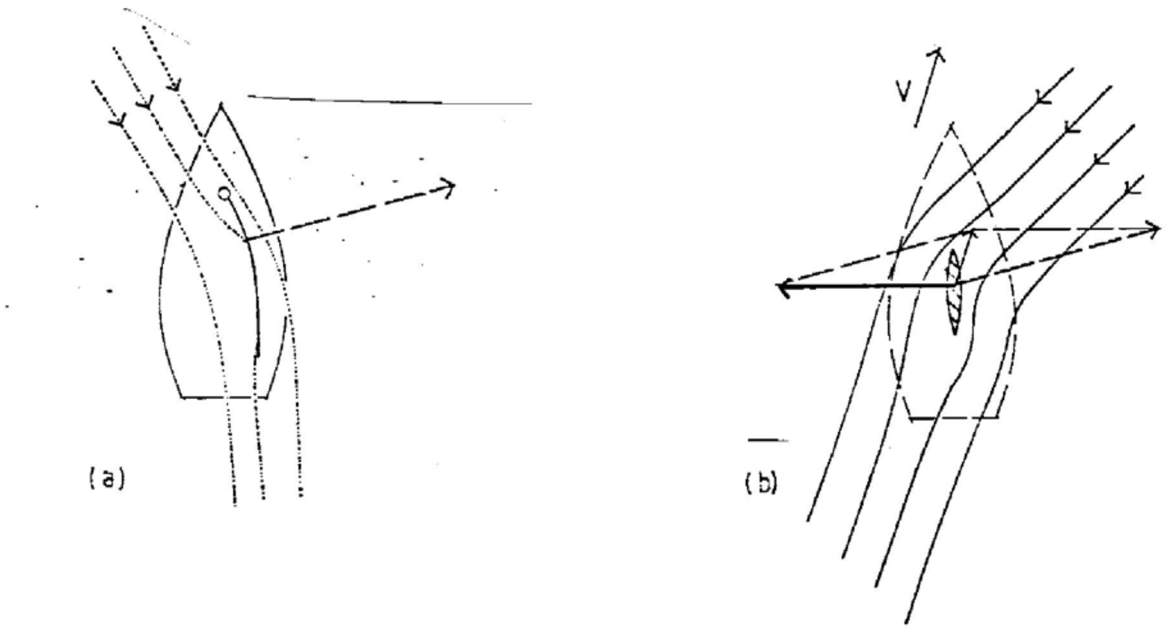
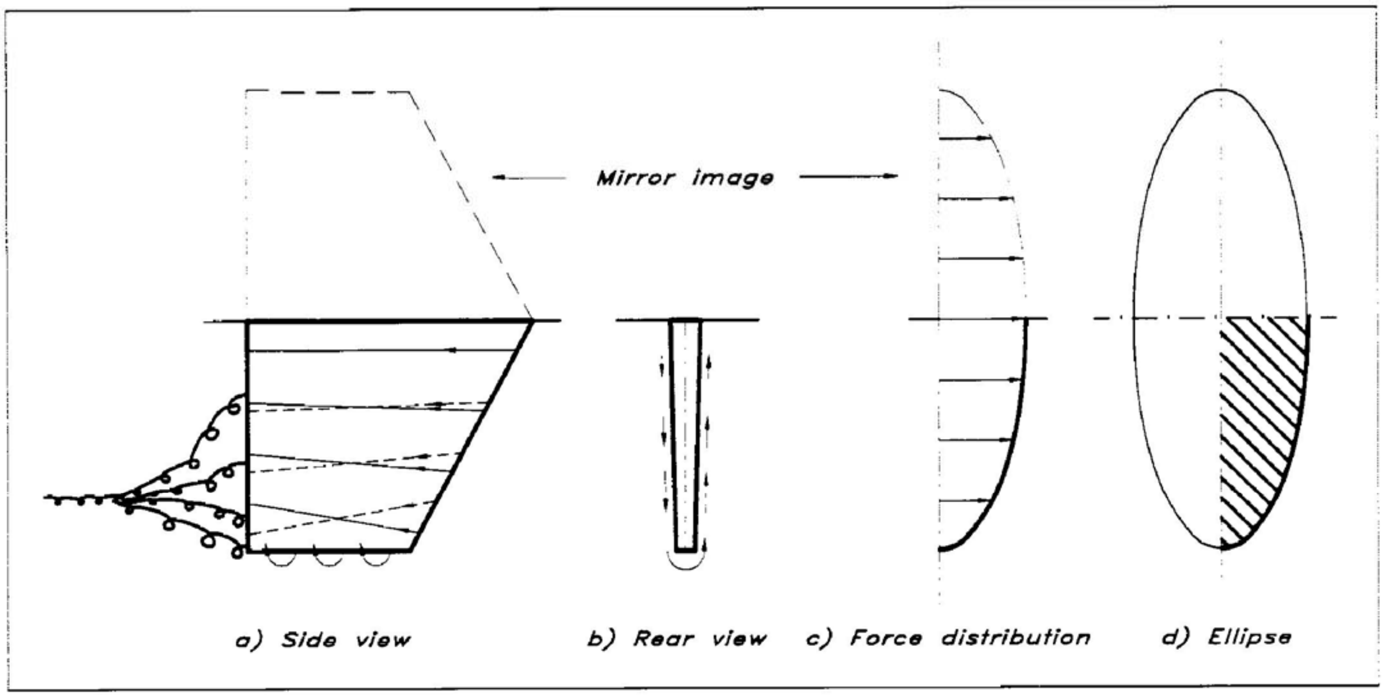


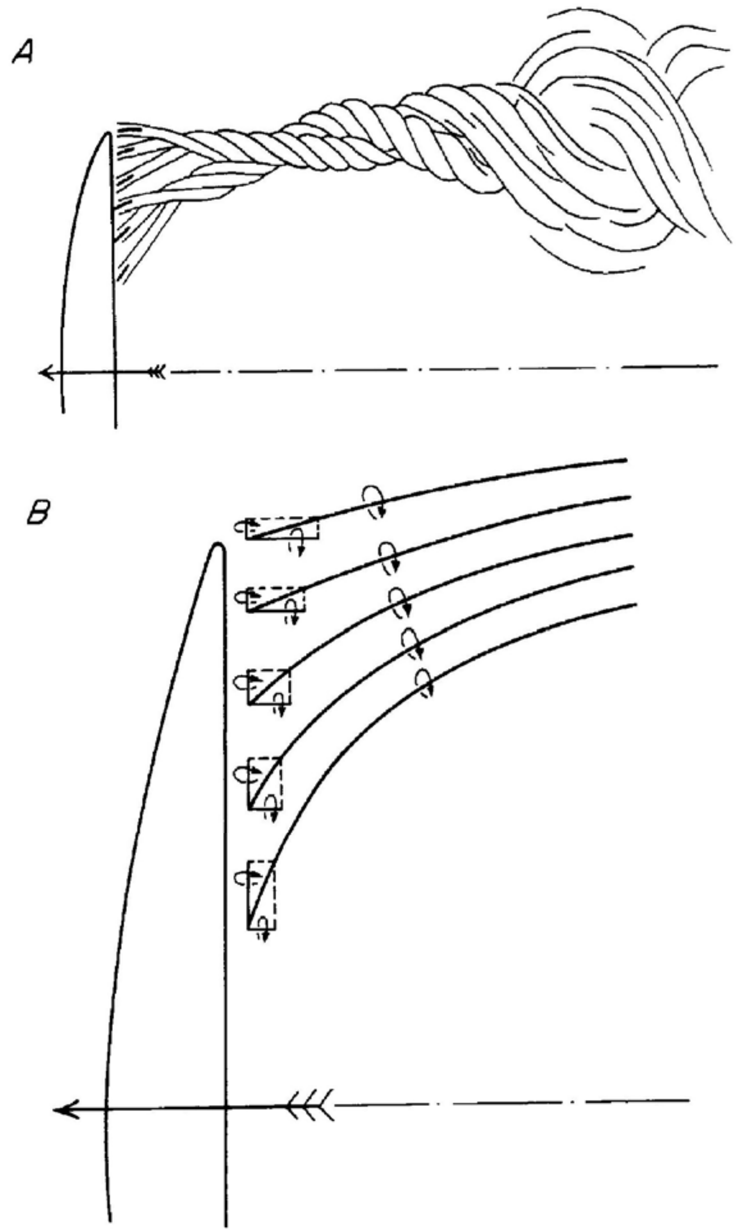
Fig 6.1 *Flow around a wing section*


Force
Suction
Leeway angle
Pressure
Flow direction
−4
−3
−2
−1
0
+1
C_p
C_p = pressure coefficient
Suction
Upper side
Lower side
Pressure

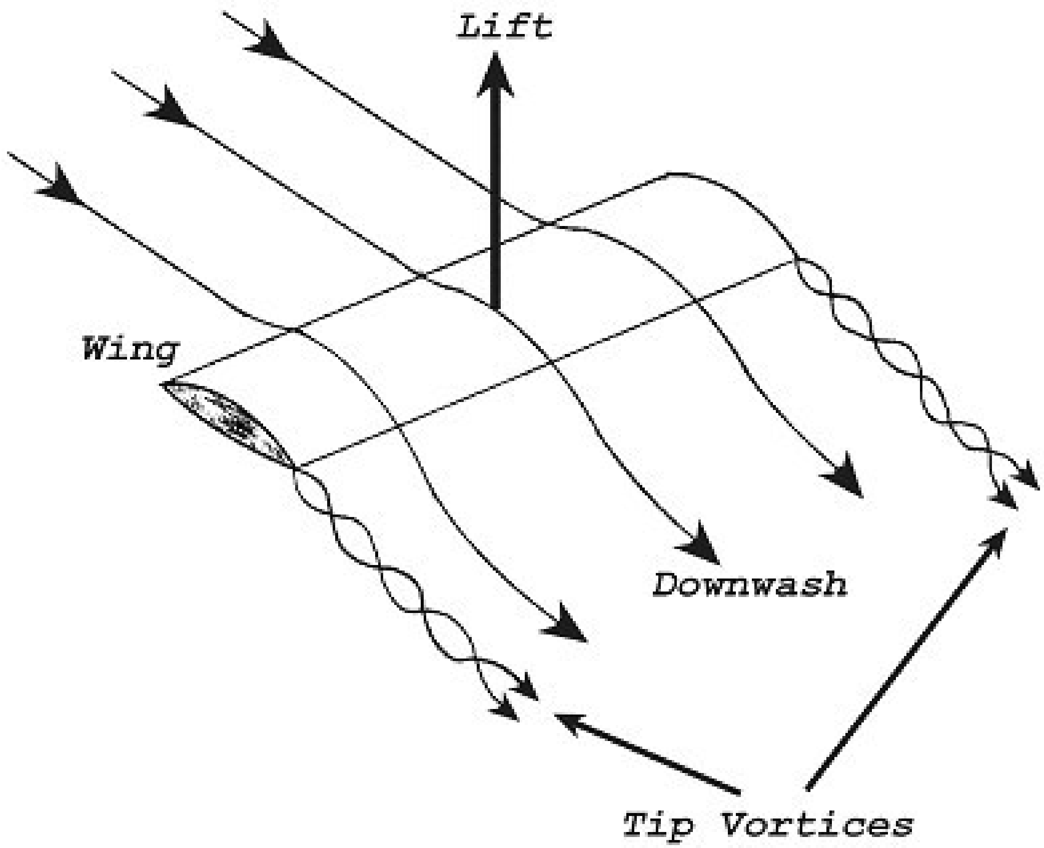
Sail and Keel Lift

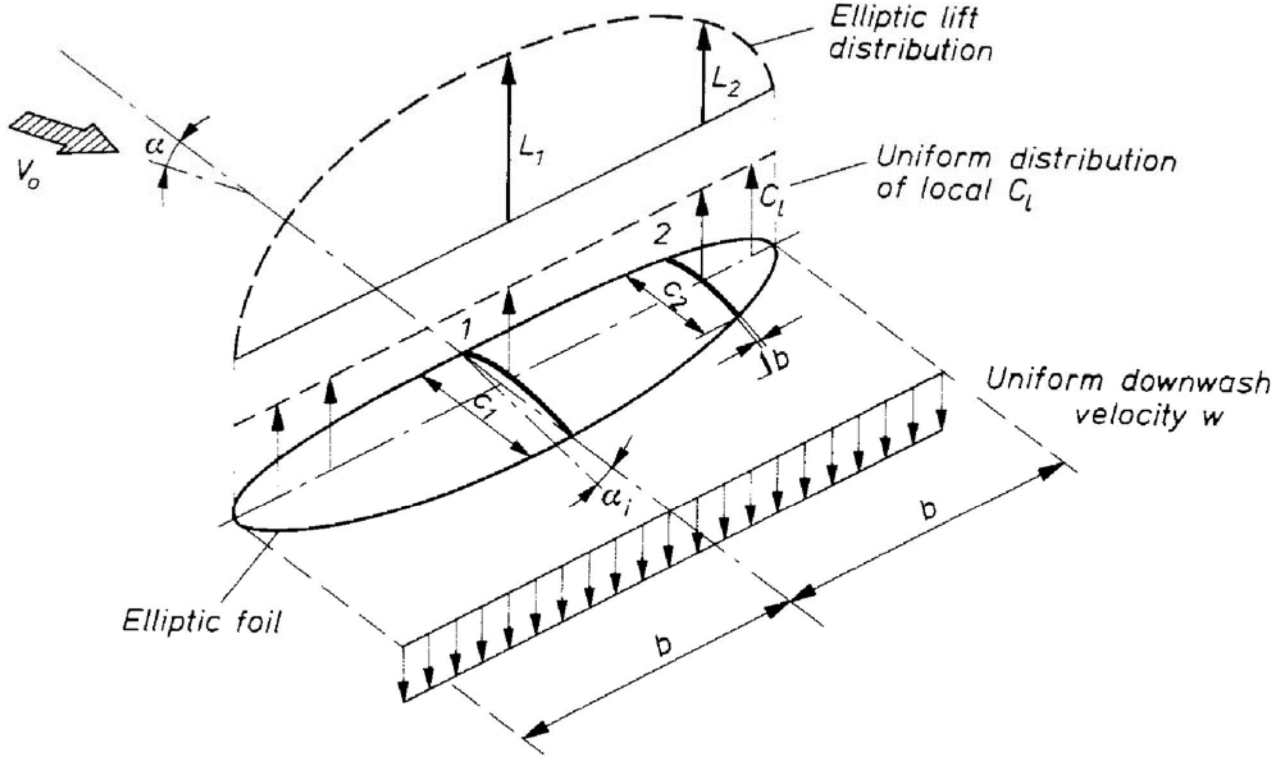


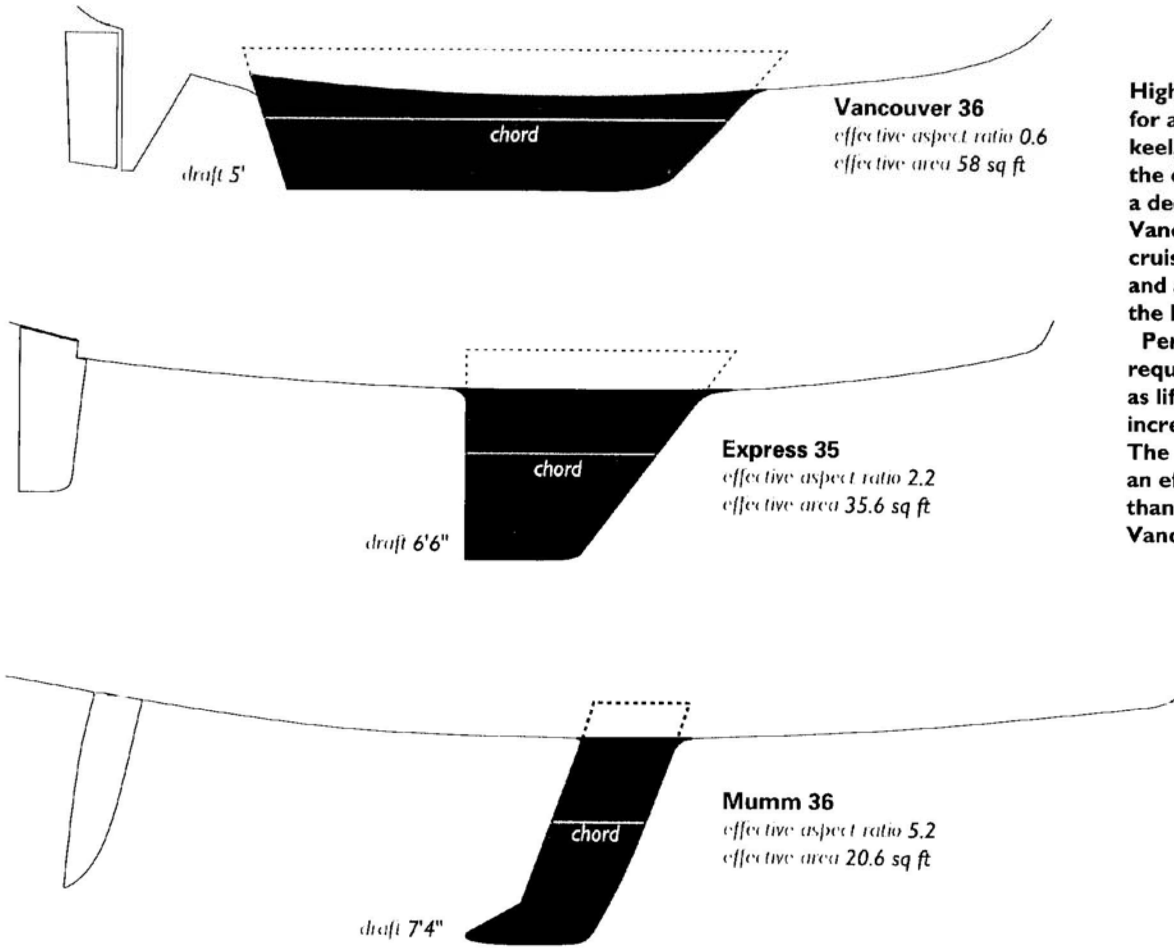

Mirror image
a) Side view
b) Rear view
c) Force distribution
d) Ellipse


A
B

Fluid flow around wing




Elliptic lift distribution
L_1
L_2
V_o
α
Uniform distribution of local C_l
C_l
1
2
c_1
c_2
b
Uniform downwash velocity w
α_i
b
b
Elliptic foil



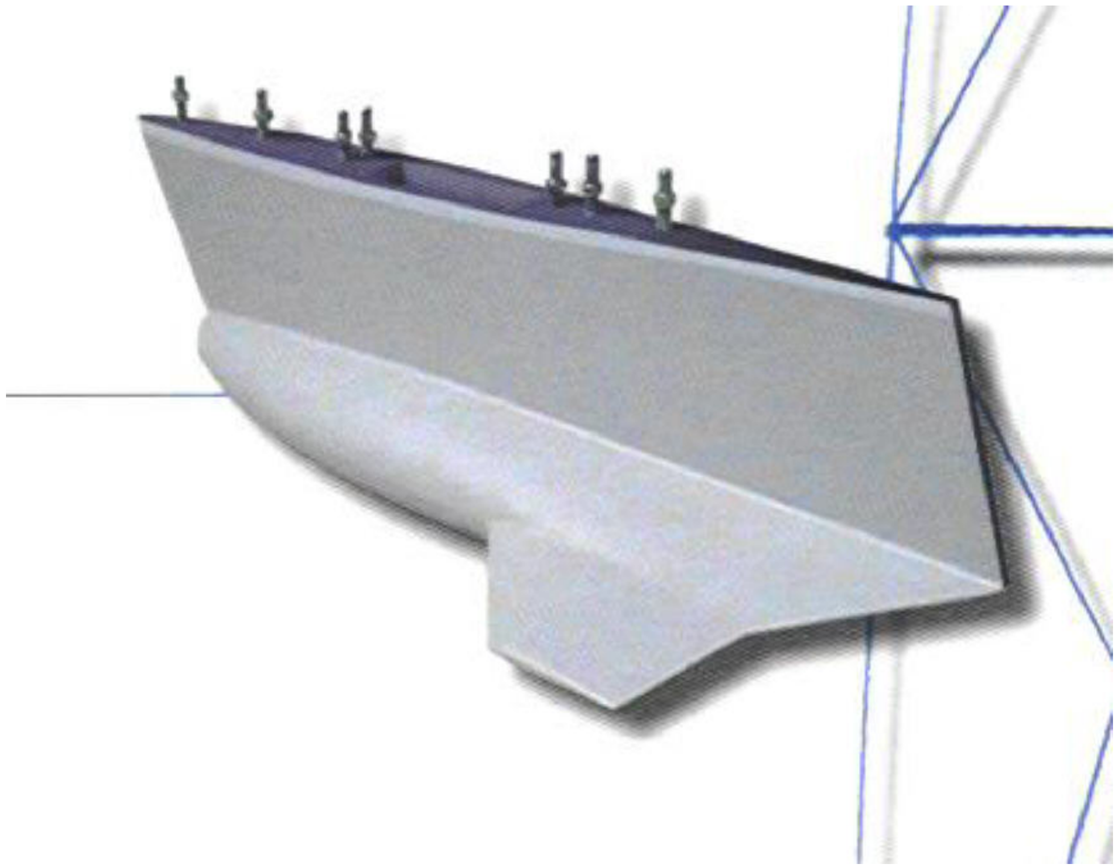
High performance calls for a higher aspect ratio keel, as illustrated by the difference between a dedicated cruiser, the Vancouver 36; a racer-cruiser, the Express 35; and a Gran-Prix racer, the Mumm 36.

Performance also requires less keel area, as lift generation increases with speed. The Mumm 36 keel has an effective area less than half that of the Vancouver 36 keel.

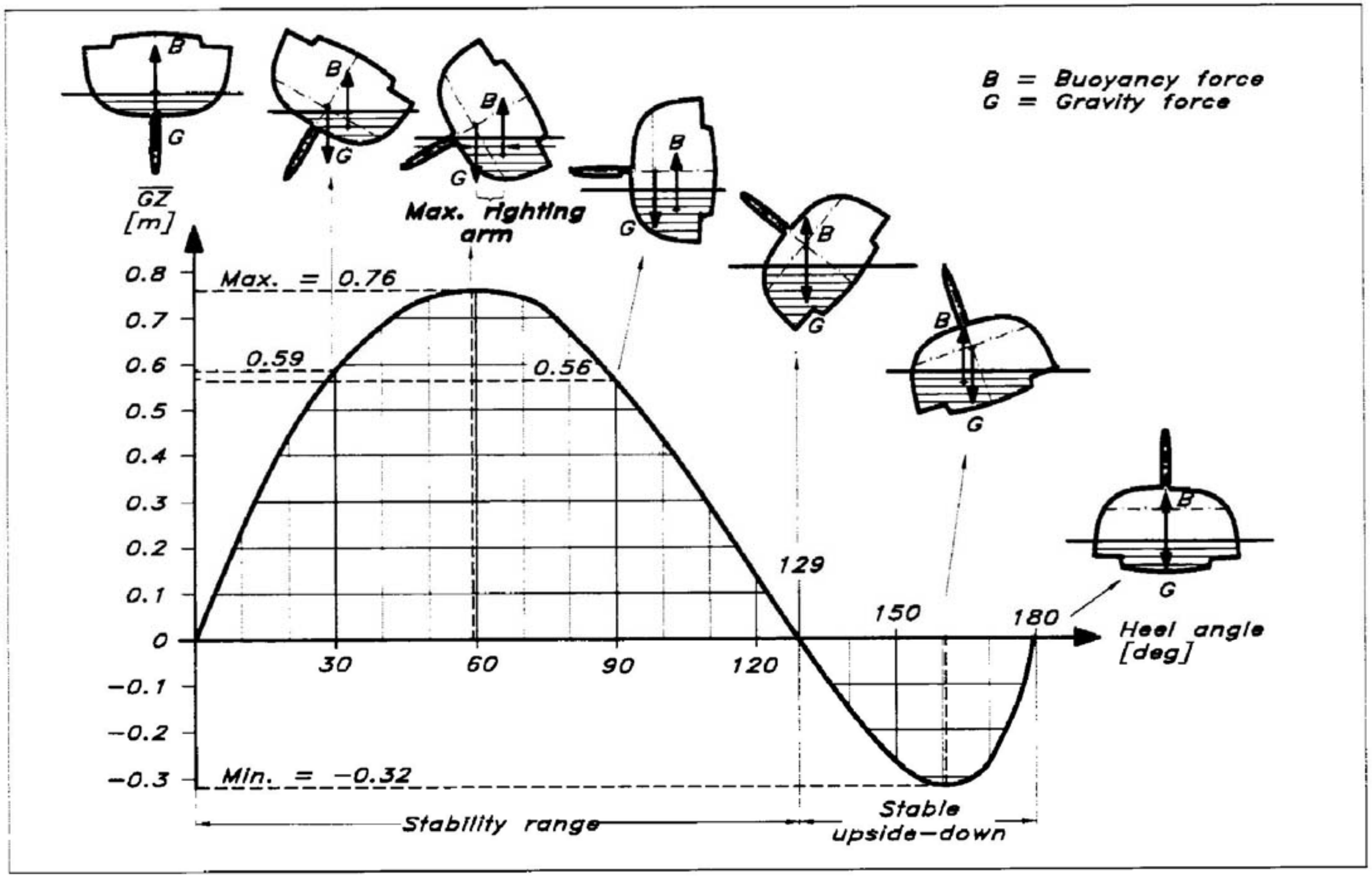
Typical Cruising Keel

Racing Keel

Shallow draft keel with wing



Keels and Stability



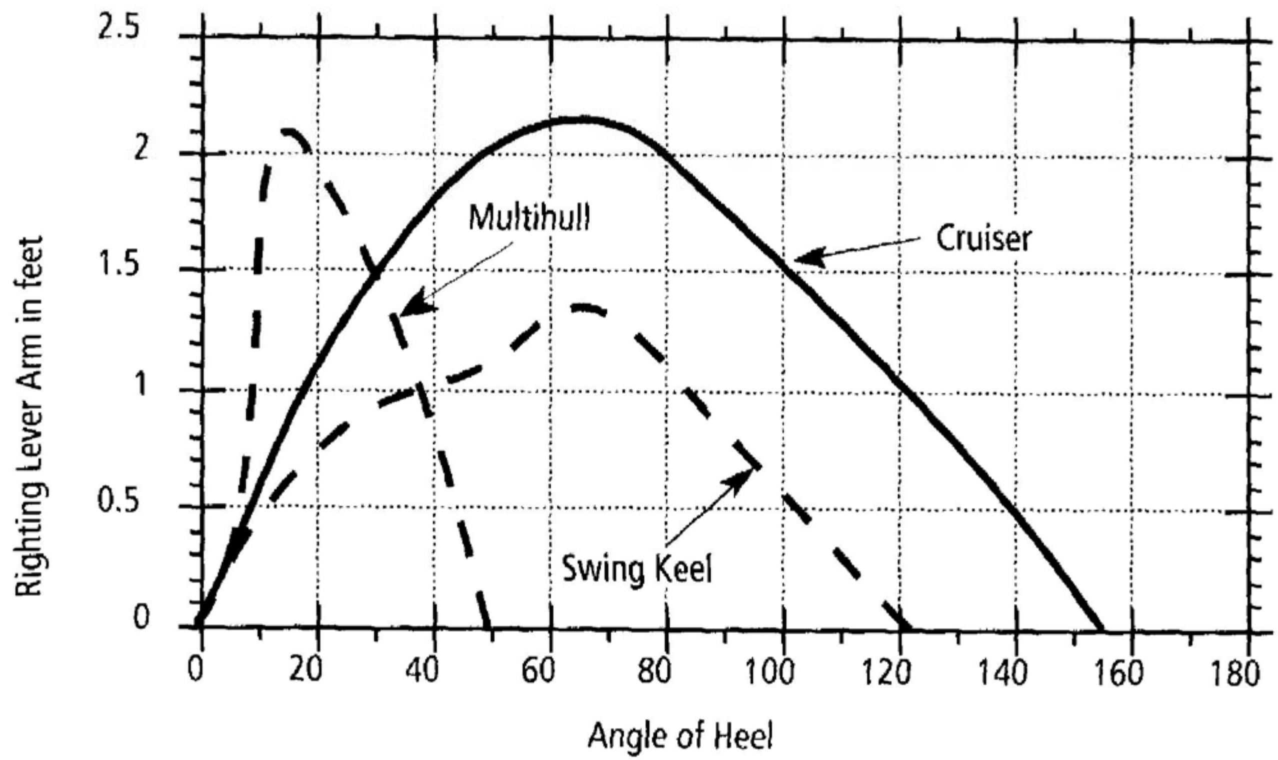
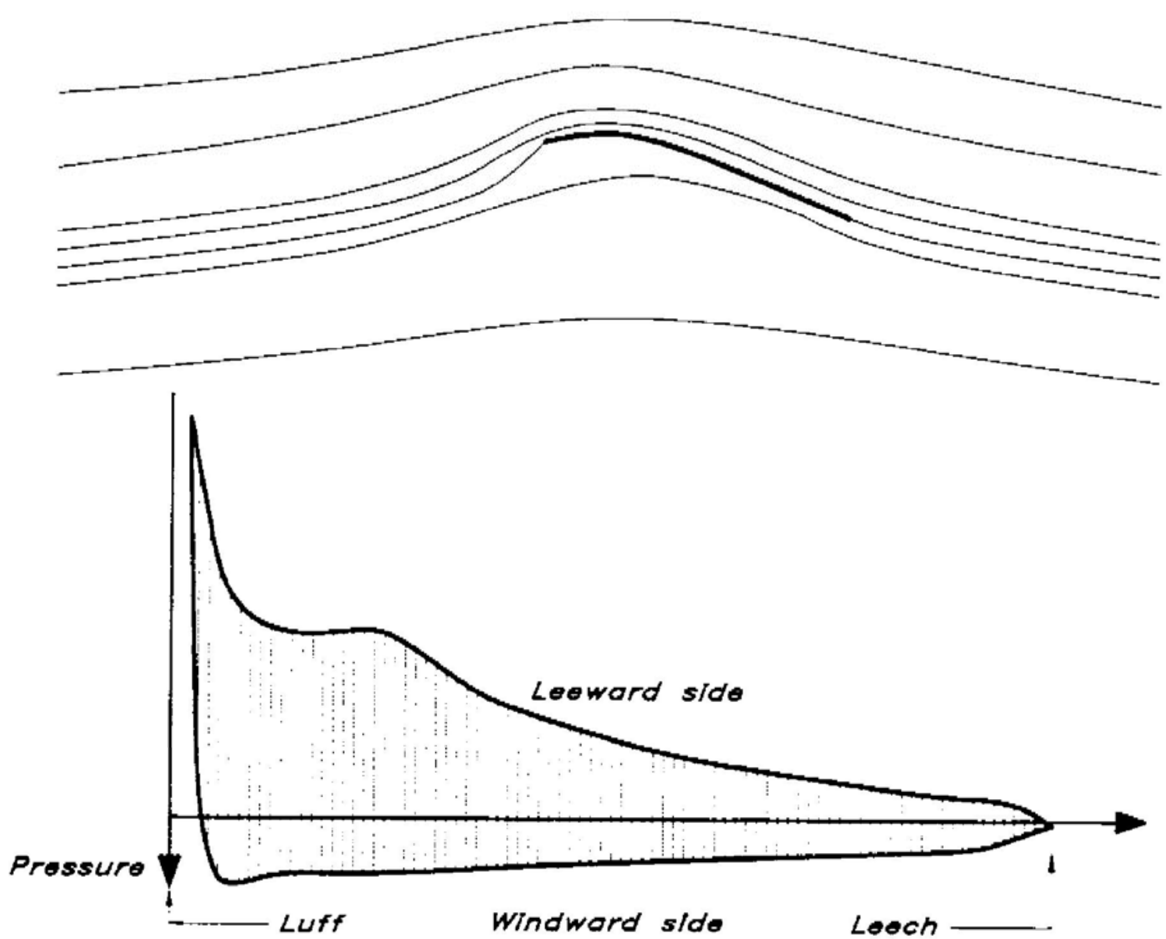


Figure 6.3 *Typical Stability Curves*


Merrill Lynch

Sails

- *Sails provide the power.*
- *Sails act like wings and provide lift and generate vortices.*
- *Ideal sail shape is different for downwind and upwind:*
  Downwind sails should be square-shaped (low aspect ratio).
  Upwind sails should be tall (high aspect ratio) to minimize vortex generation.


Leeward side
Pressure
Luff
Windward side
Leech

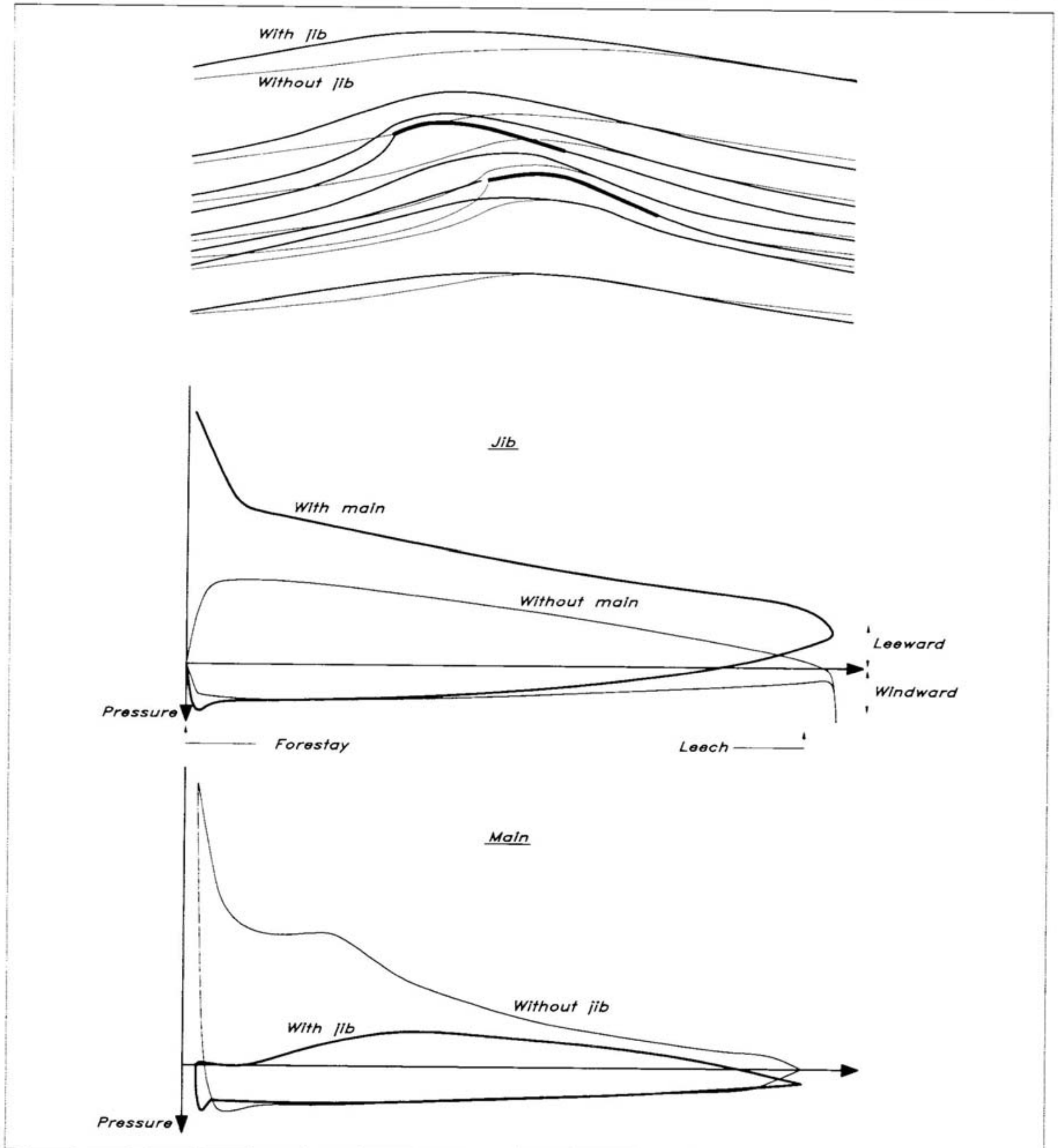

With jib
Without jib
Jib
With main
Without main
Leeward
Windward
Pressure
Forestay
Leech
Main
Without jib
With jib
Pressure

Photo 2.27A At the sailhead the air tends to flow round from windward side, where the pressure is higher, to leeward side where pressure is lower.

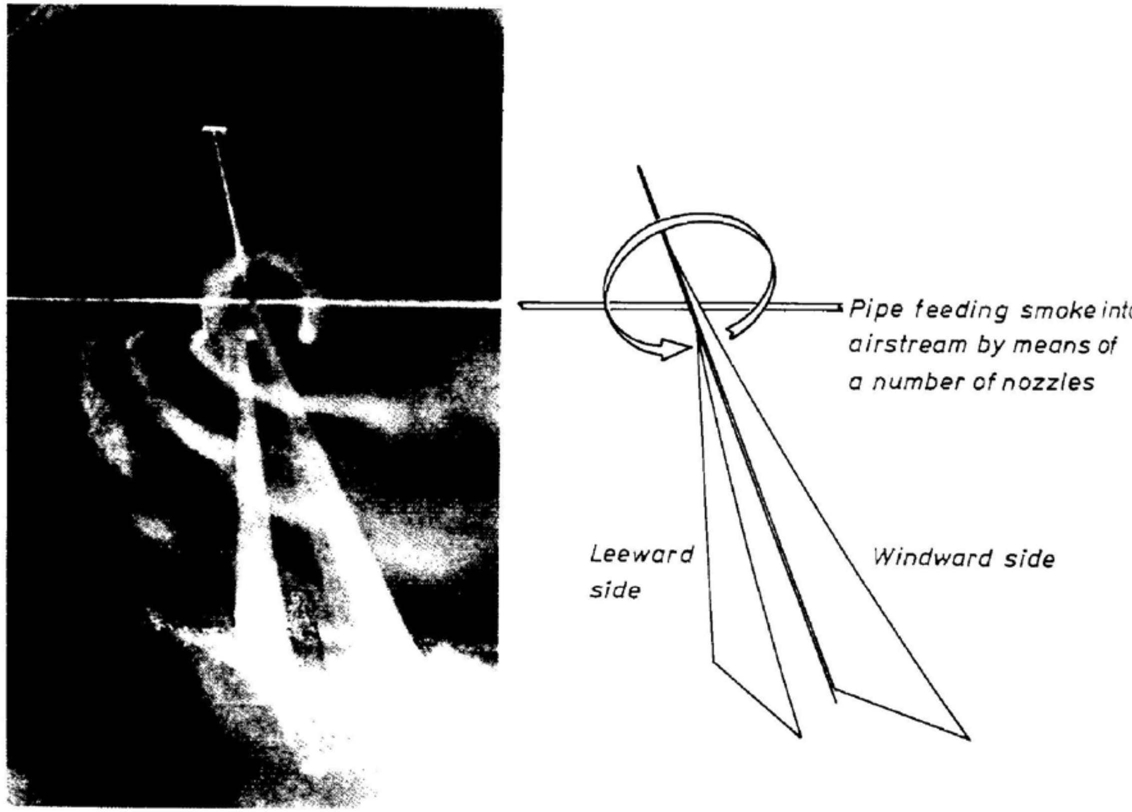


Photo 2.27B Tip vortex developing at the bottom of the Dragon keel is similar, in principle, to that shown in Photo 2.27A and C.

leadingOff

Vapor Trails

Masts of sailboats in the Volvo Ocean Race Round the World cut through fog off Cape Town on the second leg of a voyage that will cover 32,700 nautical miles.

Photograph by
Daniel Foster/DPPI

Fig. 54

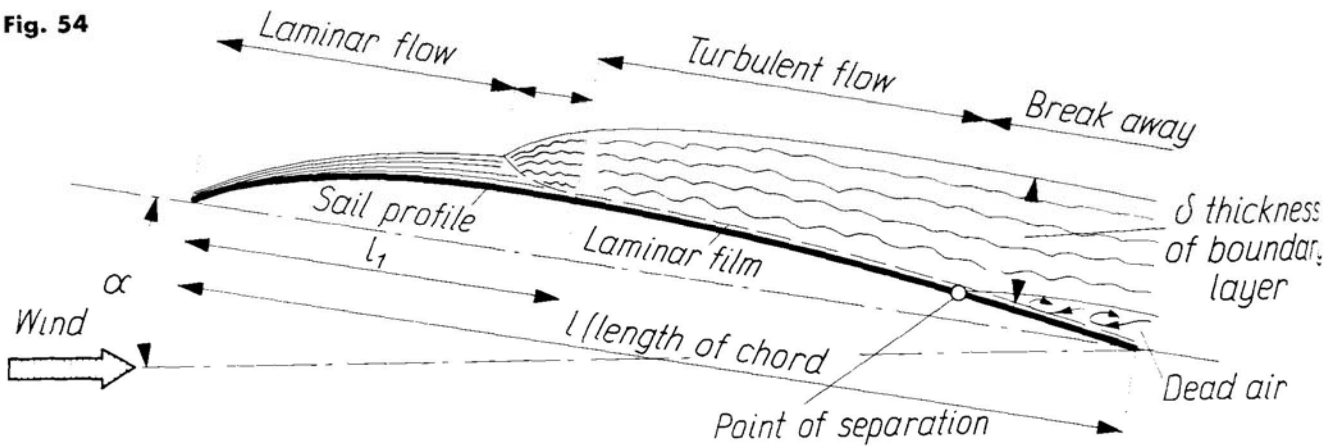
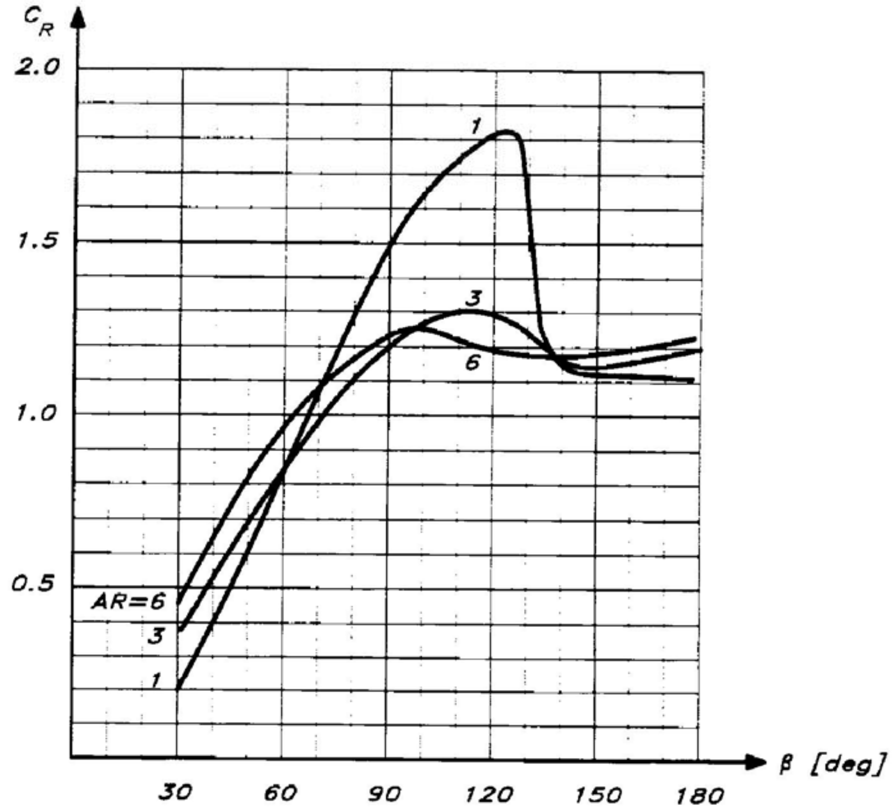

Laminar flow
Turbulent flow
Break away
Sail profile
δ thickness of boundary layer
Laminar film
l_1
α
Wind
l (length of chord
Dead air
Point of separation

Fig 7.6 *Measured influence of aspect ratio on driving force*



Velocity Prediction Program

One can try to predict the speed and direction (velocity) of a sailboat for different wind speeds and points of sail (direction with respect to the wind direction).

$$F_{drive} = R_{Total}$$
$$M_{Heel} = M_{Right}$$

$$F_{drive} = L \sin\beta - D \cos\beta$$
$$F_{Heel} = L \cos\beta + D \sin\beta$$

β = effective apparent wind angle

L = "Lift" = $C_L \, ½(\rho v^2 A)$

D = "Drag" = $C_D \, (½ \rho v^2 A)$

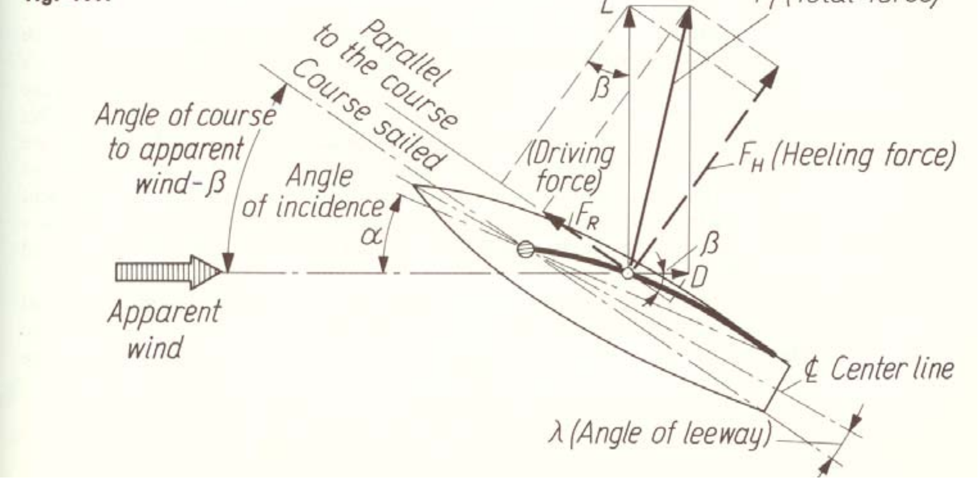
$R_{Total} = R_F + R_W + R_S + R_I + R_H + R_R$

R_F = Frictional resistance R_W = Wave resistance

R_S = Shape resistance R_I = Induced resistance

R_H = Heeling resistance R_R = Residual resistance

Fig. 49A



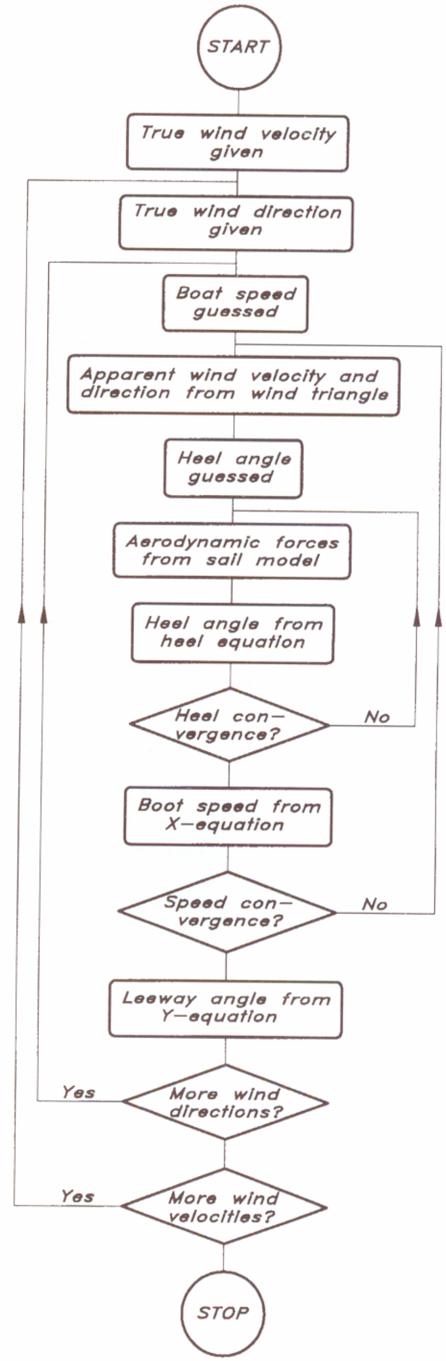
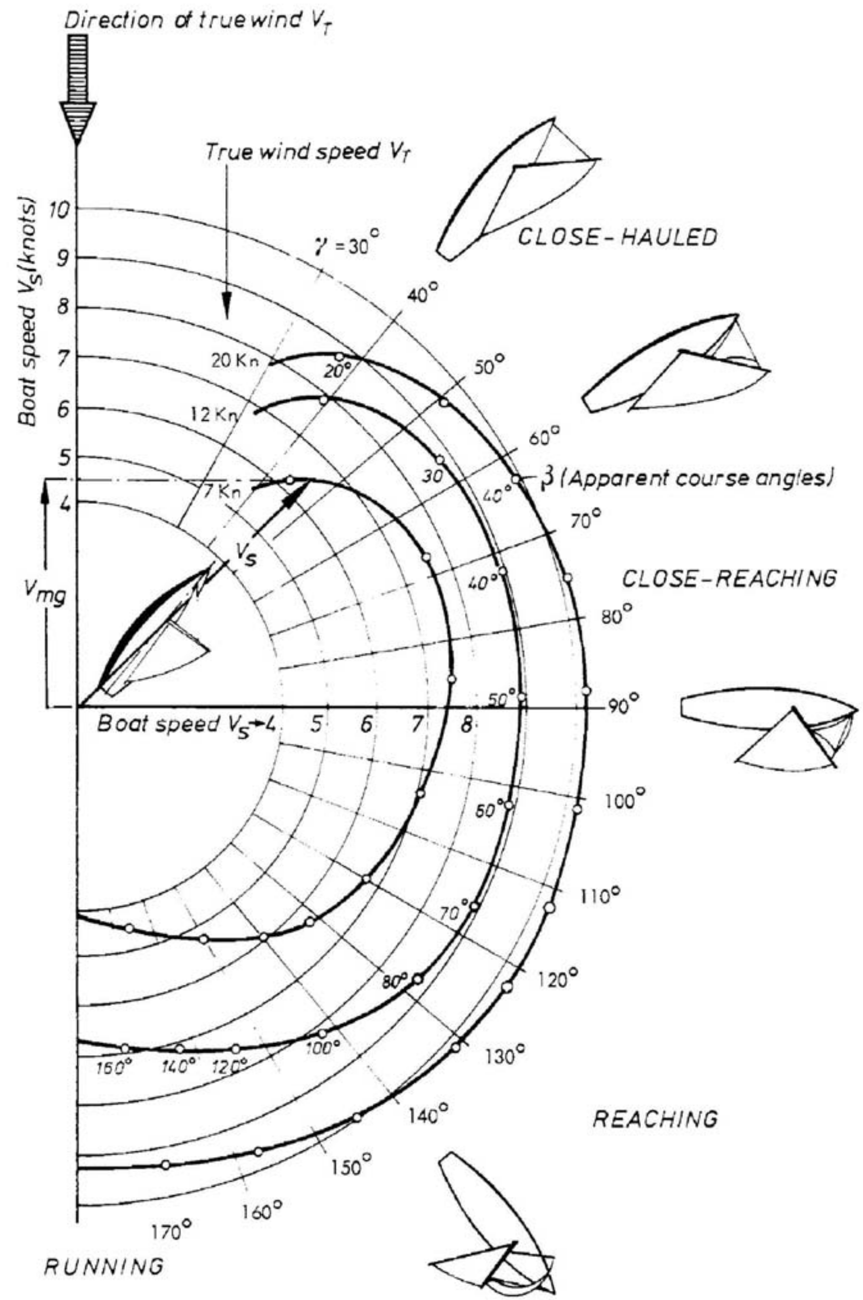

START
True wind velocity given
True wind direction given
Boat speed guessed
Apparent wind velocity and direction from wind triangle
Heel angle guessed
Aerodynamic forces from sail model
Heel angle from heel equation
Heel con-vergence?
No
Boot speed from X-equation
Speed con-vergence?
No
Leeway angle from Y-equation
Yes
More wind directions?
Yes
More wind velocities?
STOP

Fig 1.28 Performance polar diagram of a 12-Metre yacht (geometry of the velocity triangle given in Fig 1.8B).



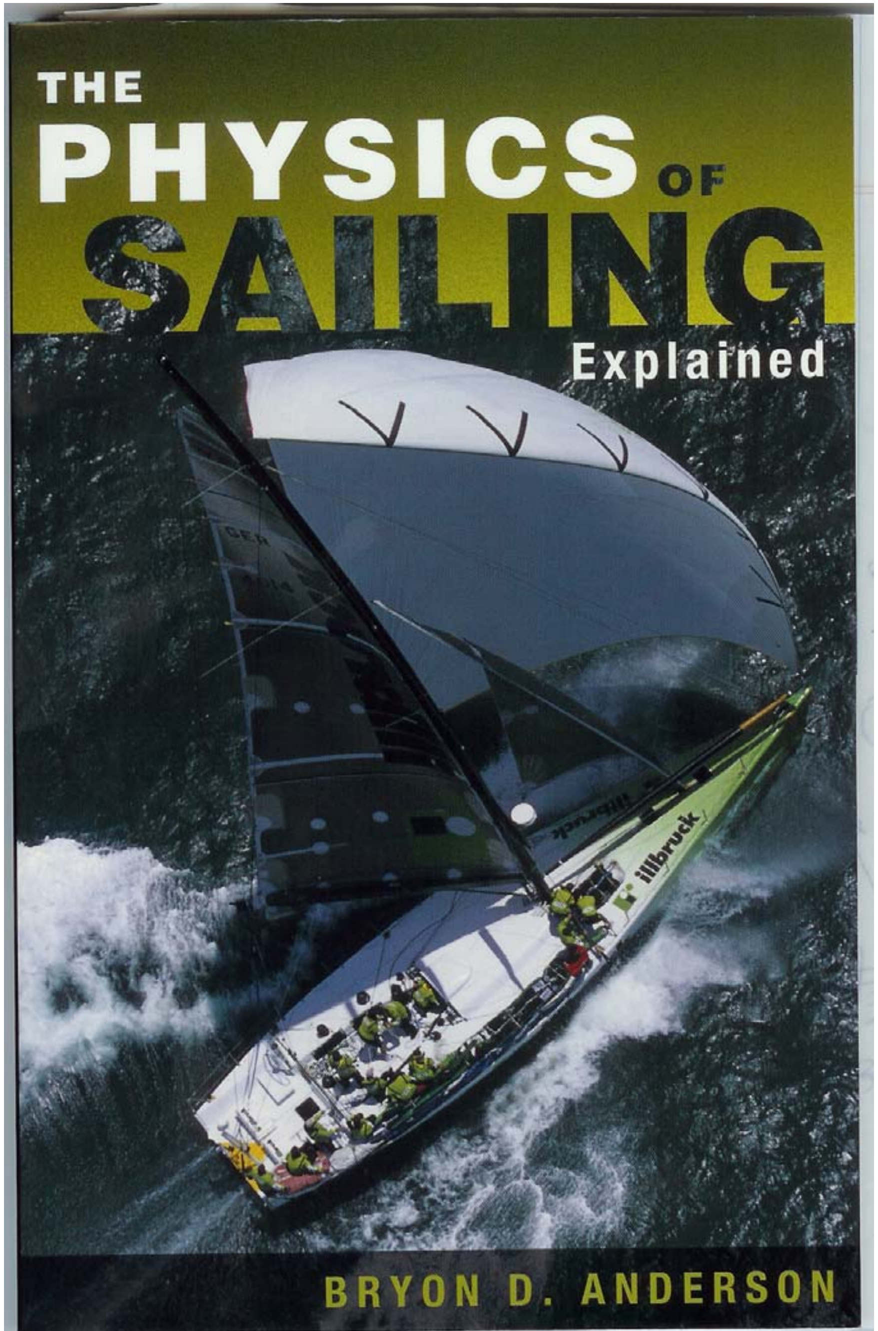
illbruck goes for more wind inshore after the start
Volvo Ocean race, Start of leg two, Cape Town, South Africa.


NZL 32
TOYOTA
TVNZ
enza
Steinlager
NEW ZEALAND
36
SEARS
TOSHIBA


SUUNTO
REPLACING LUCK.

Ensta, *the solid wing sail asymmetrical catamaran flying along in pursuit of speed records: 42.12 knots!*


Yellow Pages
ENDEAVOUR
HONDA
Yellow Pages
ENDEAVOUR


THE
PHYSICS OF
SAILING
Explained
illbruck
BRYON D. ANDERSON