From square sails to wing sails: the physics of sailing craft

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Publication date
1997

Published in
Current Science

From square sails to wing sails: The physics of sailing craft

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Through the ages

Most of the surface of our planet is covered with water, and over this water blow winds. From earliest times man has harnessed the power in the wind to transport people and goods over the water with far less effort than over land. And for centuries, sailing vessels were the only way in which distant lands separated by oceans were first discovered and later linked. Today, the most prevalent form of such transoceanic travel is to leave the water far below and to fly high above it. The direction and strength of the winds aloft still affect passage times as they did long ago, but now only in a trivial way. Given the differences in appearance, materials of construction, altitudes and speeds of operation of these two modes of transportation, one ancient and the other very modern, one could be forgiven for thinking that they could not possibly have much physics or technology in common. However, the task I have set myself here is to show you that there is in fact an intimate scientific link between them.

Let me start with a type of sailing craft in use four thousand years ago in Egypt on the Nile River which flows from South to North, while the wind blows from North to South. The sail was hoisted, as in Figure 1 to go South against the current, but was taken down when drifting North with the current. Even then, boards had to be lowered into the water, *transversely*, not longitudinally, to get a better grip on the current in order to overcome the effect of the wind blowing the opposite way on the portion of the craft above the surface (hull windage). This instantly illustrates that in this interesting system of interacting solid, liquid and gas, the speed and direction of the solid part are determined by the balance of the over and underwater forces.

These forces include underwater drag, the unwanted contributors to which are skin friction, form drag, and wave-making drag. Even though the first two grow as the square of the boat speed, they can be kept in check with a smooth and streamlined hull, and it is the third which really kills. Water waves are dispersive and propagate at speeds proportional to the square root of their wavelength. This causes the resistance due to wave making to increase very rapidly after a certain point and effectively to limit the maximum possible speed of any displacement hull to that of a wave as long as itself. This phenomenon discovered by the English engineer William Froude in the last century is depicted in Figure 2. This is why the famous Transatlantic ocean liners like the two Queens and the United States had

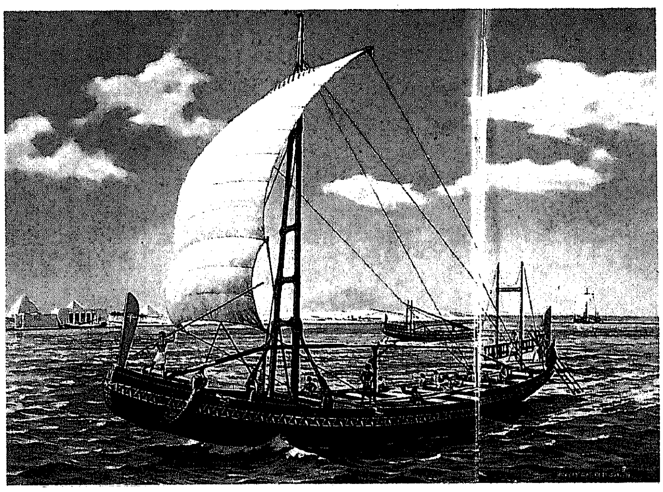

Figure 1. Ancient Egyptian square rig used on the Nile river as early as 2000 B.C.

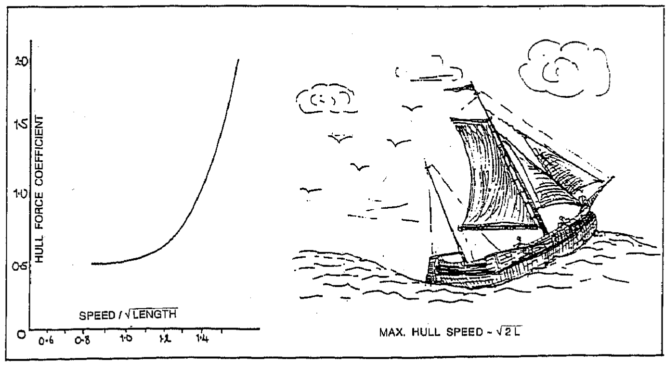

Figure 2. Wave-making drag increases catastrophically with speed as discovered by William Froude. It effectively limits the speed (measured in knots) of displacement hulls to the square root of twice their waterline lengths (measured in feet).

Based on the text of a public lecture delivered on 17 June 1997 at the University of Amsterdam on the occasion of the acceptance of the Visiting Professor chair at the Centre for High Energy Astrophysics.
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