Ship hydrodynamics

The quest for drag reduction has led to craft that are supported by hydrodynamic forces—hydrofoils—and vehicles that float across land, ice or rough seas on a cushion of compressed air—hovercraft.

Pierre Lafrance

For millenia Man has built surface vessels and used them to transport himself and his goods over water. Some appreciation for hydrodynamic forces is required to produce a functional vessel, and throughout history Man has had to rely on experience and empirical knowledge to guide his design efforts. Until recently, power for these ships has come from a limited number of sources: Sails were used to harness the winds, and men were persuaded to handle oars. However, winds tend to be unreliable, and human propulsion systems suffer from severe speed and endurance limitations. With the advent of mechanization and the discovery of new energy sources, higher speeds became attainable. With these, the effects of hydrodynamic forces become more pronounced, making it necessary to understand the patterns of water flow caused by ships to improve their performance.

This article will explore some of the hydrodynamical phenomena and forces that affect the operation of ships, especially at high speeds. Let us establish what we mean by high speed. For the purpose of our discussion, a high-speed craft is one supported by a force derived from the dynamics of the surrounding flow rather than by buoyancy. Typically, this places the bottom of the high-speed range at 20 knots. The upper limit is now somewhere between 80 and 100 knots. One knot (nautical mile per hour) is equivalent to 0.5144 m/sec, according to the textbooks. Of greater intuitive value to landlubbers such as myself is the fact that the maximum motor vehicle speed allowed on US highways is approximately 48 knots.

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This article is not meant to be exhaustive—the space available is too limited to do justice to ship hydrodynamics. However, I hope to provide enough detail to leave the reader with some feel for the subject. As much as possible I will avoid mathematical formulations, which abound in fluid mechanics, and emphasize physical arguments. (One exception is the Box on page 37.) I therefore ask the indulgence of professionals in this field, who may fail to find their favorite topic discussed, and of the mathematically minded, who may have honed their analytical skills on fluid mechanics.

Displacement vessels

To creatures accustomed to bipedal (and, in our days, motor) locomotion, ship motion presents a new world of problems. Ground locomotion involves action–reaction forces localized at very specific points: the contact area between our feet and the ground, or between tires and the road. Consider the ship, however. Immersed in a yielding medium, its hull is exposed to various forces, such as viscous and pressure forces. The nature and magnitude of these can change markedly with small changes in flow conditions. Turning maneuvers, especially with the heavier vessels, must be accomplished with calculated accuracy, because the craft's own inertia can cause serious overshoots. At high speeds, the water flow may separate from the appendages or hull, changing the force characteristics and in some instances greatly affecting the characteristics of control surfaces. To point out how the various hydrodynamic forces arise and affect the craft I shall discuss displacement ships, hydrofoil craft and air-cushion vehicles. One example of the latter is the US Navy's amphibious assault landing craft JEFF B, shown in figure 1.

The largest and oldest category of surface ships is that of displacement vessels, which derive their supporting force from buoyancy, the hydrostatic pressure resulting from the weight of the displaced water. From the hydrodynamic point of view, a common factor of all displacement hulls is that they present a large area of contact with the surrounding fluid. The motion of a body through a fluid medium gives rise to pressure gradients within the medium. This is true whether or not the fluid possesses viscosity, a material property akin to the frictional resistance of solid mechanics. That pressure gradients are generated should not be surprising: They provide the necessary accelerations to remove the fluid that is ahead of the body and place it in the body's wake.

It can be shown that a uniformly translated body suffers no hydrodynamic drag by virtue of its motion through an infinitely extended inviscid fluid. This surprising result, known as "d'Alembert's paradox," runs contrary to everyday experience. We will see its resolution below, in the discussion of the effect of viscosity. In the proximity of a free surface—in this case, the air–water interface—hydrodynamic drag occurs even in inviscid fluids. A moving body carries with it a pressure field, as mentioned above. Near the free surface, this pressure causes local elevations of the water surface, because the free surface can not sustain pressure discontinuities and is constantly at atmospheric pressure.

The ship's dynamic pressure field

Riding on an air cushion is the US Navy's amphibious assault landing craft, JEFF B. Compressed air is supporting the 150 000-kg vehicle, which is about 25 m long. Hovercraft such as this and other alternatives to traditional ships raise challenging problems. Figure 1

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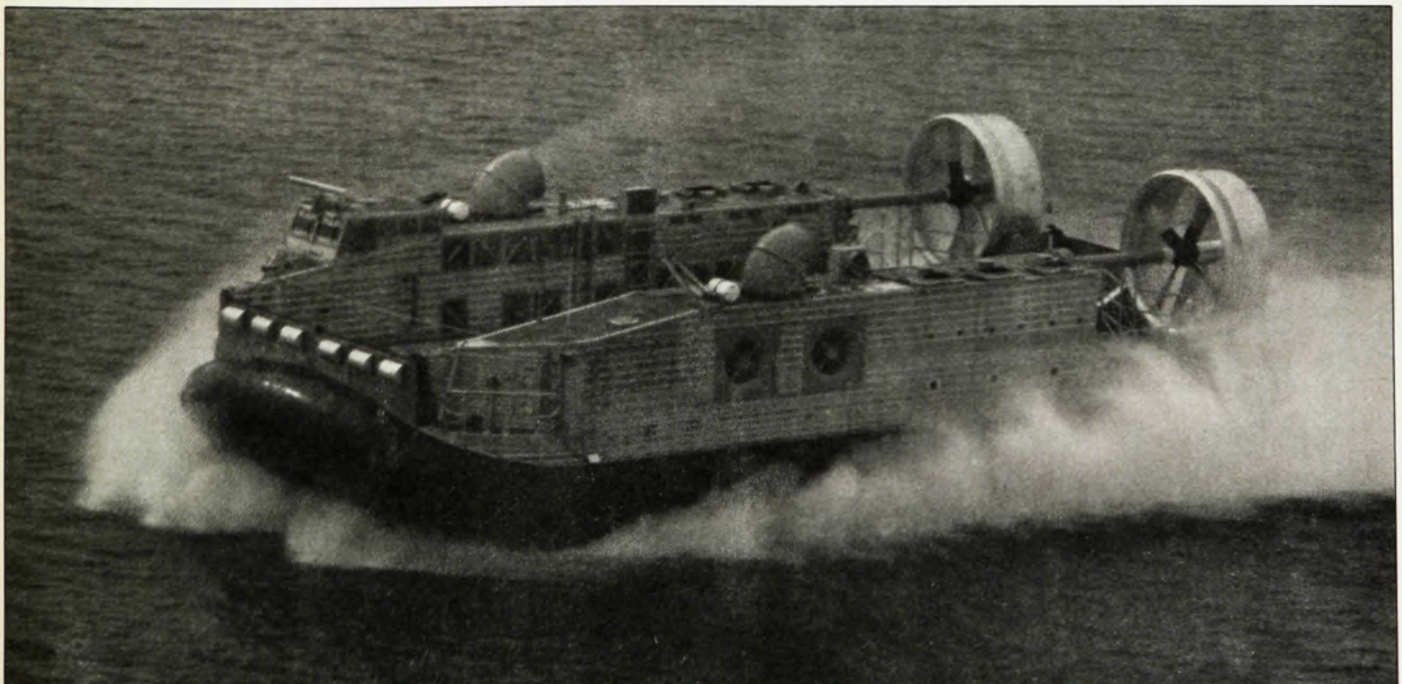
causes local surface elevations so as to produce a hydrostatic pressure—through the weight of the displaced fluid—to maintain the surface at atmospheric pressure. The ship, with its pressure field, plows through the water, causing a moving surface deformation. The surface reacts dynamically to this disturbance by oscillating under the opposing forces of gravity and buoyancy.

What I have described, of course, is the way in which ship waves are produced. These waves radiate away from the ship, carrying with them some energy. This energy flux away from the ship represents an effective "wave drag." The energy radiated away per unit time can be equated to the product of the "wave drag" and the ship speed. Wave drag is a force felt by any body in motion near the surface, whether fully submerged or not. Because the wave pattern depends on the pressure field, which in turn depends on hull shape, it is reasonable to expect that a suitable modification of the hull shape will minimize the wave drag. Such thinking has led to the development of the modern "bulbous bow," a good example of improved design resulting from an understanding of fluid dynamics.

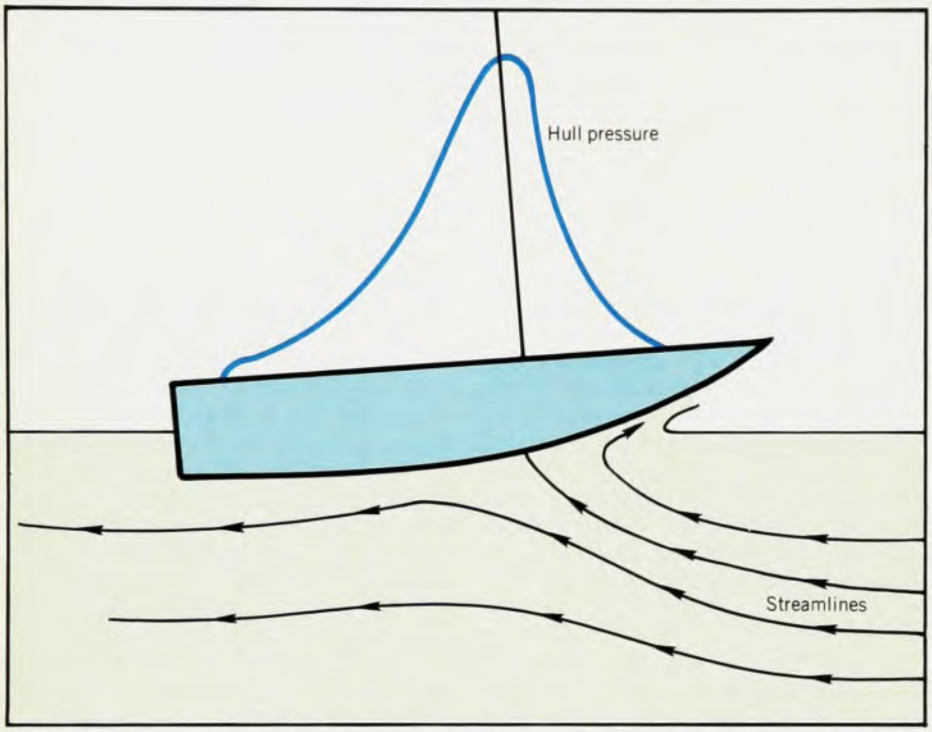
Causes of drag

Viscosity, however small in quantity, has a marked effect on body forces. Viscous fluids have the ability to tranfer momentum along velocity gradients. If we view viscous flow as a superposition of thin fluid layers coupled by friction, we realize that the motion in one layer will entrain the fluid in adjacent layers through viscous coupling. The layer-coupling strength is the viscosity, and its magnitude determines how much momentum is transferred from one layer to the next. When a viscous fluid is in contact with a solid surface, the fluid in intimate contact with the surface sticks to it; this is true no matter how small the viscosity is. The layer of fluid in immediate contact with the body therefore moves with the body. The degree to which the momentum diffuses away from the body is a function of the viscosity and of the local velocity gradients. Through this mechanism, outlying fluid layers are entrained by those closer to the body, and a velocity profile is established in the fluid

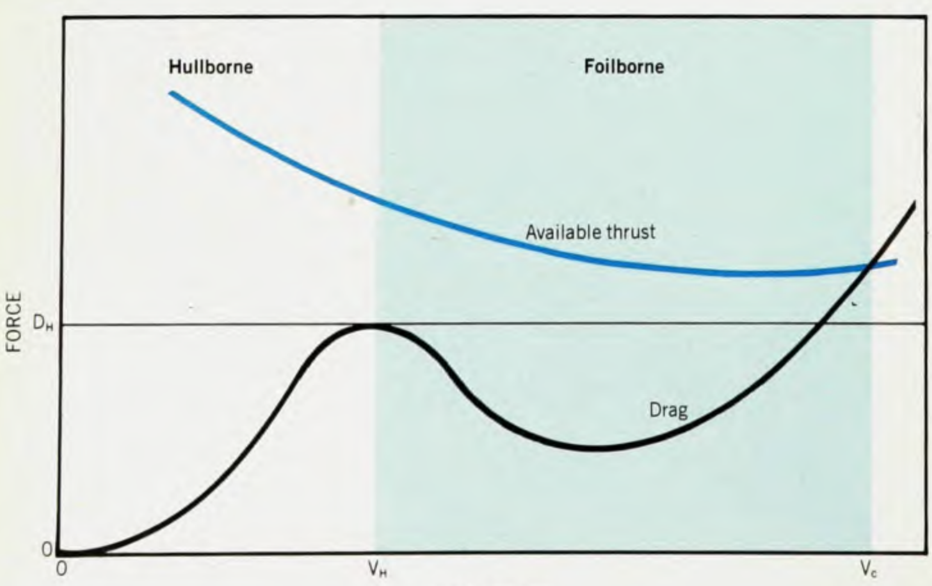


near the body. The fluid velocity, equal to the ship velocity at the hull, gradually decreases over a distance known as the boundary-layer thickness. The momentum flow away from the ship represents a resistance force: the viscous skin friction drag. The resolution of d'Alembert's paradox therefore is this: Because all everyday fluids are viscous, we do not experience dragless motion through them.

The viscous boundary layer—the flow region close to the hull in which viscous effects are important—is greatly affected by the ambient pressure field generated by the body's motion through the fluid medium. On the aft portion of the ship's hull, where the adjacent flow is decelerated and the local pressure increases, a phenomenon known as "boundary-layer separation" is likely to occur. As the fluid in the boundary layer flows into regions of progressively increasing pressure, the retarding effect of the pressure gradient combines with the viscous friction to slow down the fluid. The part most affected is that which possesses the least amount of momentum: the boundary-layer flow.



The pressure distribution on a high-speed planing hull provides the force that supports the craft. The colored line shows the hull pressure along the axis indicated. Dynamic forces raise the craft partly out of the water, which reduces its drag. Figure 2



Typical drag and thrust characteristics for a hydrofoil craft. At speeds above the "hump" speed V_H, the hull is pushed out of the water; V_c is the cruise speed. Figure 3

Eventually, the retarding forces succeed in first stopping and then reversing the flow at the body surface, creating a region of recirculation, or separation, over which the flow reestablishes itself.

This does not occur with an ideal inviscid fluid, because the fluid gains some momentum ahead of the body, is accelerated past the body, and decelerates under the influence of the positive pressure gradient. The effect is like that of a conservative force, and after the body's passage the fluid is returned to its initial state. Viscosity, however, causes a continual irreversible drain of momentum away from the boundary layer. As a result, the fluid in it lacks the necessary momentum to overcome the pressure hill. The outcome is that the pressure within the separated zone is lower than the pressure ahead of the body. The net pressure difference results in a drag force on the body, called "form drag" or "separation drag."

The major components of the ship resistance are

- form drag,
- viscous skin-friction drag and
- wave drag.

The large wetted area of displacement hulls presents a large surface for boundary-layer development, and for the form and wave pressures to act. The resulting drag is proportional to the wetted area, the water density and the square of the ship speed. Drag essentially limits the speed at which a ship can operate. The maximum speed attainable is that at which the total drag force—a quadratic function of speed—equals the maximum thrust available.

Speed increases can be achieved either by an increase in engine thrust or by a decrease in drag. The former alternative implies larger and weightier propulsion plants, which have several disadvantages, among them being greater fuel consumption and an increase in drag caused by the additional weight. Drag reductions can be achieved in a variety of ways, including modifications to the flow boundaries or to the fluid itself. Small amounts of certain polymers added to a fluid can radically reduce the drag, as reported in the "Search and Discovery" section of PHYSICS TODAY, March 1978. Good hull design can also lower the drag. For ships traveling at sufficiently high speeds, however, another possibility exists: Dynamic pressures, developed on hulls and appendages at high speeds, can support a large portion of the craft's weight, thereby decreasing the required buoyant force and hence wetted area. These dynamic forces can be high enough to raise part of the craft out of the water. This reduces the craft's wetted area and consequently the overall drag. On a planing hull this advantage is limited by the need to maintain a wetted area large enough to support the craft; this is the area over which the pressure acts, as illustrated in figure 2. For hydrofoils and air-cushion vehicles however, the quest for drag reduction has been carried much further.

The hydrofoil: bare essential

A basic problem of ship design is to minimize hydrodynamic drag, so as to leave a significant portion of available thrust to provide increased speed for the craft. The classic streamlined hull shape has evolved as a compromise between the need to support the ship's weight by water displacement and the need to minimize drag. The hydrofoil craft carries this idea to the extreme of minimizing the wetted surface area necessary to support the load at high speeds by means of small submerged wings—hydrofoils—attached to the hull with struts. At high speeds these foils can develop sufficient lift to support the craft's structure above the water surface.[1] The ship's power is then available for acceleration to much higher speeds, where foil drag itself becomes the limiting factor.

Figure 3 illustrates the powering operation of this type of craft. At low speeds, the craft is hullborne and the drag (hull drag) increases quadratically with speed until the "hump" speed V_H is reached. The drag in this low-speed portion of the curve is mostly attributable to the hull, because the craft operates as a displacement vessel. At the hump speed, enough lift is generated by the foils to push the hull out of the water, thereby decreasing the overall drag. This drag reduction is what gives rise to the characteristic hump on the curve. At higher speeds the craft is foilborne and the drag is entirely due to the foils and supporting struts. This drag, small at first, also increases as the square of the speed. The colored line in the figure represents an idealization of the total thrust available from the ship's engines. The amount by which the total available thrust exceeds hump drag is called the "thrust margin"; this should be sufficiently large to allow such accelerations as may be required. The intersection of the thrust line with the foil-drag curve determines the equilibrium cruise speed V_c, at which thrust balances drag and no further acceleration is possible.

The maximum attainable cruise speed to a hydrofoil craft is therefore determined by the thrust that can be delivered and by the drag characteristics of the foil system. At cruise speed, the craft is often said to be "flying" on its foils, in an obvious analogy with aircraft, which utilize similar lift and control surfaces. Let us now turn to these foils for a closer look.

Bodies placed into a uniform flow are subject to two types of forces[2,3]:

- The drag force, due to viscosity, acts in the direction of the flow; more complicated flow phenomena, such as streamline separation from the body, can also generate appreciable drag.[4]
- A lift force, perpendicular to the incoming flow, may be generated on suitably shaped bodies such as aerofoils or hydrofoils. These lifting foils become extremely useful when the lift-to-drag ratio can be made large, 10 or more for hydrofoils.

These forces result from unsymmetrical pressure distributions on the body surface, and are equivalent to momentum transfer from the surrounding medium to the body. Because momentum flux is a quadratic function of flow speed, the hydrodynamic forces and pressures also vary as the square of the flow speed. Although we commonly think of lift as pointing "up," lift forces play important roles in ship propellers, airscrews and various control surfaces such as rudders and flaps, where they usually act in horizontal directions. An important theorem credited to Nikolai Joukowski relates the lift force per unit length on a two-dimensional object, L, to the velocity circulation on an arbitrary contour C enclosing the object,

$$L = -\rho V_0 \oint_C \mathbf{V} \cdot d\mathbf{l}$$

where V_0 is the uniform velocity far from

The wave resistance of an air-cushion vehicle

A good example of the type of mathematical analysis used in ship hydrodynamics is the treatment of the wave resistance of an air-cushion vehicle by Lawrence Doctors and Som Sharma, which led to the results shown in figure 6.

Consider a frame of reference (x,y,z) attached to an air-cushion vehicle moving with speed V_0 in the x direction, with z being vertically upward. Let us neglect viscosity and assume that the flow is irrotational:

$$\text{vorticity} = \nabla \times \mathbf{V} = \mathbf{0} \qquad (1)$$

where $\mathbf{V}$ is the velocity field. This can be expressed as the gradient of a scalar quantity Φ, the velocity potential:

$$\mathbf{V} = \nabla\Phi \qquad (2)$$

Conservation of mass implies that $\nabla \cdot \mathbf{V} = 0$, so that the velocity potential satisfies Laplace's equation

$$\nabla^2\Phi = 0 \qquad (3)$$

The vehicle is modeled by a prescribed localized pressure distribution, $p(x,y)$, in motion with speed V_0 over the water surface ($z = 0$). The waves that result are described by a surface-deformation amplitude such that the free surface is described by an equation of the form $z = z(x,y,t)$.

Basically, what follows is a perturbation solution. We assume that the pressure $p(x,y)$ is small and consider only the first terms in expansions in a small quantity ϵ,

$$z(x,y,t) = \sum_{j=1}^{\infty} \epsilon^j \eta_j(x,y,t) \qquad (4)$$

$$\Phi(x,y,z,t) = \sum_{j=1}^{\infty} \epsilon^j \phi_j(x,y,z,t)$$

We now drop the redundant subscript. The linearized kinematic condition on the surface (at $z = 0$) is

$$\frac{\partial \phi}{\partial z} + V_0 \frac{\partial \eta}{\partial x} = \frac{\partial \eta}{\partial t} \qquad (5)$$

This condition equates the surface fluid velocity to the displacement rate of surface elements. The linearized dynamic condition on the surface, Bernoulli's equation, is

$$\frac{\partial \phi}{\partial t} - V_0 \frac{\partial \phi}{\partial x} + \frac{p}{\rho} + g\eta = 0 \qquad (6)$$

where ρ and g are the fluid density and the gravitational acceleration, respectively. Equations 5 and 6 can be combined to eliminate explicit dependence on the surface amplitude η at $z = 0$.

$$\frac{\partial^2 \phi}{\partial t^2} + V_0^2 \frac{\partial^2 \phi}{\partial x^2} - 2V_0 \frac{\partial^2 \phi}{\partial x \partial t} - \dot{V}_0 \frac{\partial \phi}{\partial x} + g\frac{\partial \phi}{\partial z} = \frac{V_0}{\rho}\frac{\partial p}{\partial x} \qquad (7)$$

In water of depth d, the normal velocity must vanish on the bottom,

$$\left[\frac{\partial \phi}{\partial z}\right]_{z=-d} = 0 \qquad (8)$$

The solution for the velocity potential turns out to be

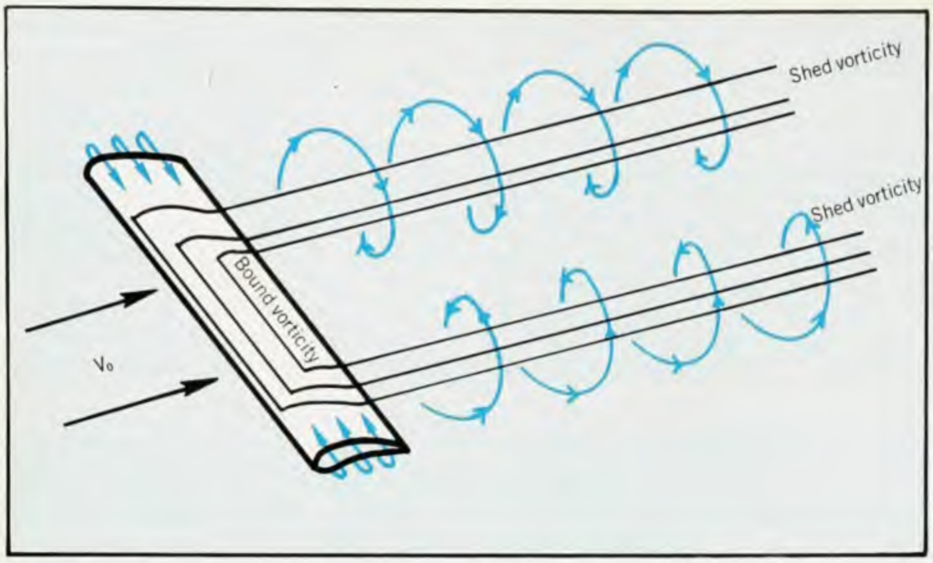
$$\phi(x,y,z,t) = \frac{i}{4\pi^2\rho} \int_S\int p'dS' \int_0^t V_0(\tau)d\tau \int_{-\infty}^{\infty} dw \int_{-\infty}^{\infty} du \, \frac{w \cdot \cosh[k(z+d)]}{\sqrt{gk \cdot \tanh(kd)} \cdot \cosh(kd)} \cdot \sin[\sqrt{gk \cdot \tanh(kd)} \cdot (t-\tau)] \cdot \exp[i\{w[x - x' + s(t) - s(\tau)] + u(y-y')\}] \qquad (9)$$

where S is the surface area over which the pressure is prescribed, w and u are the longitudinal and transverse wavenumbers, $k^2 = u^2 + w^2$, and x' and y' are dummy coordinates in the vehicle's frame of reference.

Equation 6 can be used to recover the surface-wave amplitude. The wave resistance R of the pressure distribution is defined as the horizontal component of the force acting on the free surface:

$$R = \int_S\int p(x,y)\frac{\partial n}{\partial x}dxdy$$

Typical results are shown in figure 6 for a set of given pressure distributions. The strong correlation between cushion-pressure distribution and wave resistance raises the interesting prospect of designing the cushion shape to minimize the drag.



The effects of finite span on a lifting surface such as a hydrofoil. The colored lines trace the vorticity, which is bound on the foil. At the tip it is shed into the passing stream, leaving the induced swirling currents shown in the vehicle's wake. Figure 4

the body and ρ is the density of the fluid.

This flow circulation, responsible for the lift, can be represented with the help of Stokes's theorem by lines of vorticity, the curl of the velocity field, aligned along the wingspan. We pause here to note briefly a useful heuristic analogy between our example and a current-carrying wire in a uniform magnetic field. Although there is no physical connection between them, the lifting wing in uniform flow is similar to a current-carrying wire perpendicular to a uniform externally imposed magnetic field. The interaction between the current (vorticity) and the external magnetic (velocity) field results in a force perpendicular to both the current (vorticity) and the external field. Joukowski's theorem forms the basis of lifting flow theory and of well developed mathematical formulations used in the design of wing sections, propellers and hydrofoils.

For wings of finite span, three-dimensional effects are important. The vorticity lines can not suddenly terminate at the wing tips; we shall see that the vorticity is actually shed from the foil and carried away by the main flow. This may be easier to visualize in terms of pressure and velocity. The lift force is caused by the fact that the fluid at the top surface is at a lower pressure than the bottom. For a foil of infinite span, the resulting flow is two-dimensional, with no spanwise variations. For a foil of finite span, however, the pressure difference between the top and bottom surfaces induces a flow across the wing tip, from the bottom to the top. The net effect is a spanwise flow toward the tip on the high-pressure side, and away from the tip on the opposite surface. At the wing's trailing edge these two opposing spanwise velocity fields meet as a surface of tangential flow discontinuity, forming a vortex sheet with vorticity rolls aligned in the direction of the main flow. Thus the vorticity associated with the foil's lift is all shed downstream, as shown in figure 4.

The individual vortex lines join a short distance aft of the trailing edge, producing two contra-rotating vortices that entrain the surrounding fluid in long trailing spirals. The strength (specifically, the vorticity) of these swirling currents is proportional to the craft weight, equal to the lift force. Left to themselves, these vortices slowly descend, ultimately to be dissipated by viscosity. The long lifetimes of the manmade atmospheric disturbances from airplane-generated vorticity can be particularly dangerous for small aircraft flying in the wake of larger ones, a condition likely to occur around airports, where several aircraft in succession must use the same landing strip. Landing patterns accordingly have been devised to minimize the risk of such aerodynamic interference by requiring the heavier airplanes—the producers of strongest vorticity—to make their final approach at low altitude. Their vorticity wakes therefore remain out of the way of smaller airplanes and can reach ground level in a relatively short time after the airplane has passed.

Bubble trouble

The spontaneous formation of the gaseous phase due to a reduction of the local pressure below vapor pressure, a phenomenon known as "cavitation," can and indeed does occur over certain portions of bodies immersed in high-speed flow.[5] The pressure distribution over the body is a function of the incoming flow characteristics and of the body shape. The local pressure on the body in excess of ambient pressure (atmospheric plus hydrostatic) is expressed as a *pressure coefficient* C_p, a quantity defined by

$$C_p = \frac{p - p_{\text{ambient}}}{\frac{1}{2}\rho V_0^2}$$

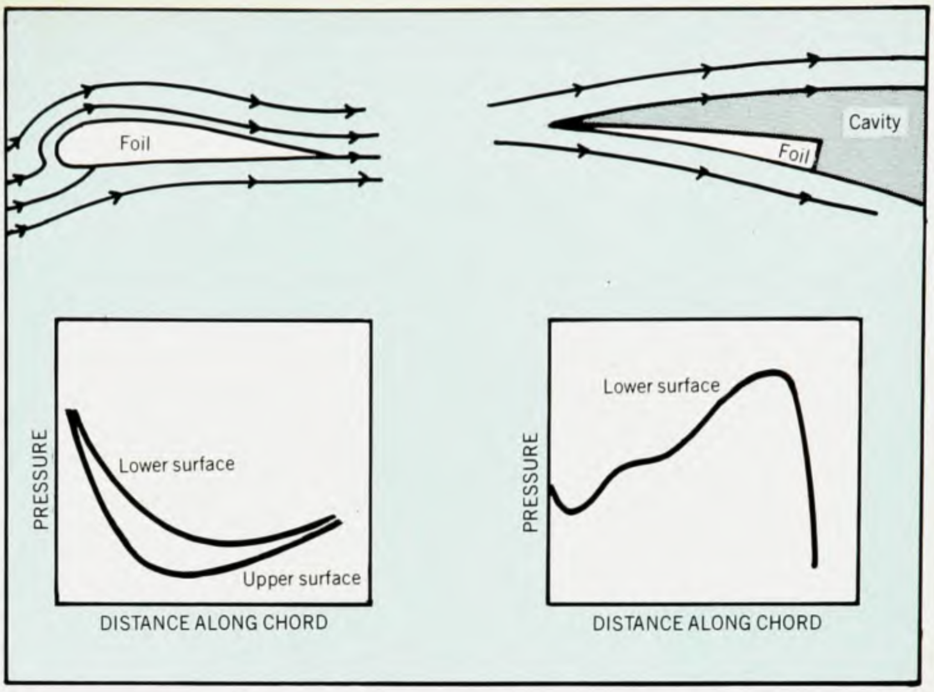
where p is the local pressure, a function of position and speed, and C_p is a function of position and body shape. Places where C_p is negative develop pressures that decrease with increasing speed. For sufficiently high speeds, the local pressure can be as low as the ambient fluid's vapor pressure, so that a vapor cavity forms. The pressure within the cavity remains constant at the vapor pressure, and the external flow readjusts accordingly.

At the threshold speed for the inception of cavitation, bubbles form sporadically, accompanied by rather violent pressure fluctuations on or very near the body surface. A small region of the flow at vapor pressure may sustain the formation and growth of cavitation bubbles, which are then continuously entrained by the flow to regions of higher pressure, where they collapse violently. The speed at which cavitation develops depends strongly on body shape, and "delayed cavitation" shapes can be designed for operation at high speeds.

At speeds much higher than that required for cavitation inception, the low-pressure region extends over an appreciable portion of the body, and cavitation-bubble collapse occurs far downstream in the body's wake. A large continuous cavity then envelops the body. When this "supercavitating" state is reached, cavitation erosion is minimal and the flow in the immediate vicinity of the body and cavity is steady. A serious consequence of cavitation for lifting surfaces such as hydrofoils is that the vapor cavity in contact with the foil necessarily reduces the wetted area and therefore greatly affects the force distribution, usually resulting in a poorer lift performance. For this reason, cavitation-free operation is a desirable objective.

For speeds at which cavitation can no longer be avoided, typically 50 knots or over for hydrofoils, cavitation must be accepted, and foil sections are designed to "fly" with their suction side in permanent contact with a cavity. It is not surprising that supercavitating foil sections are markedly different from their fully wetted cousins. Figure 5 illustrates the similarities and differences in shape, flow conditions and pressure distributions for the two types of hydrofoils. In the fully wetted case, the foil thickness distribution and camber determine the pressure distribution on the foil. The rounded leading edge reduces flow accelerations that would lead to boundary-layer separation at low speeds and cavitation at higher speeds. For the supercavitating foil, the leading edge is very sharp. A cavity springs from this point and extends over the entire upper surface of the foil, which is therefore maintained at vapor pressure. The lower surface is usually cambered and shaped to produce the required lift. The shape of the upper surface is somewhat irrelevant, the only constraints being that it be below the cavity surface, and that the foil thickness be sufficient to provide the strength and rigidity required.

Operating near the air–water interface—as hydrofoils do—is not without hazards. Maintaining a vapor cavity close to the surface invites ventilation, the sudden creation of an air passage that admits atmospheric air to into the low-pressure cavity. Because atmospheric pressure is two orders of magnitude higher than water-vapor pressure, the consequences on lift can be disastrous, particularly if ventilation were to occur spontaneously on a craft at full speed. The use of ventilation fences or guards on the strut discourages the occurrence of this phenomenon. An alternative approach is to introduce ventilation deliberately and maintain an air flow to the foil in the hope of obtaining a steady, predictable flow condition. The mechanics of ventilation is a little-understood subject. Theoretical studies are few, and experimental measurements on ventilated bodies are difficult.



Two hydrofoils. The subcavitating foil (left) is designed for fully wetted operation; the supercavitating foil (right) operates with its upper surface in contact with a vapor cavity. Streamlines indicate flow patterns; the graphs show pressure distributions. Figure 5

Floating on air

A latecomer to the growing family of high performance craft, the air-cushion vehicle, also known as a "hovercraft," holds much promise for the future. We shall adopt the following definition for a hovercraft:

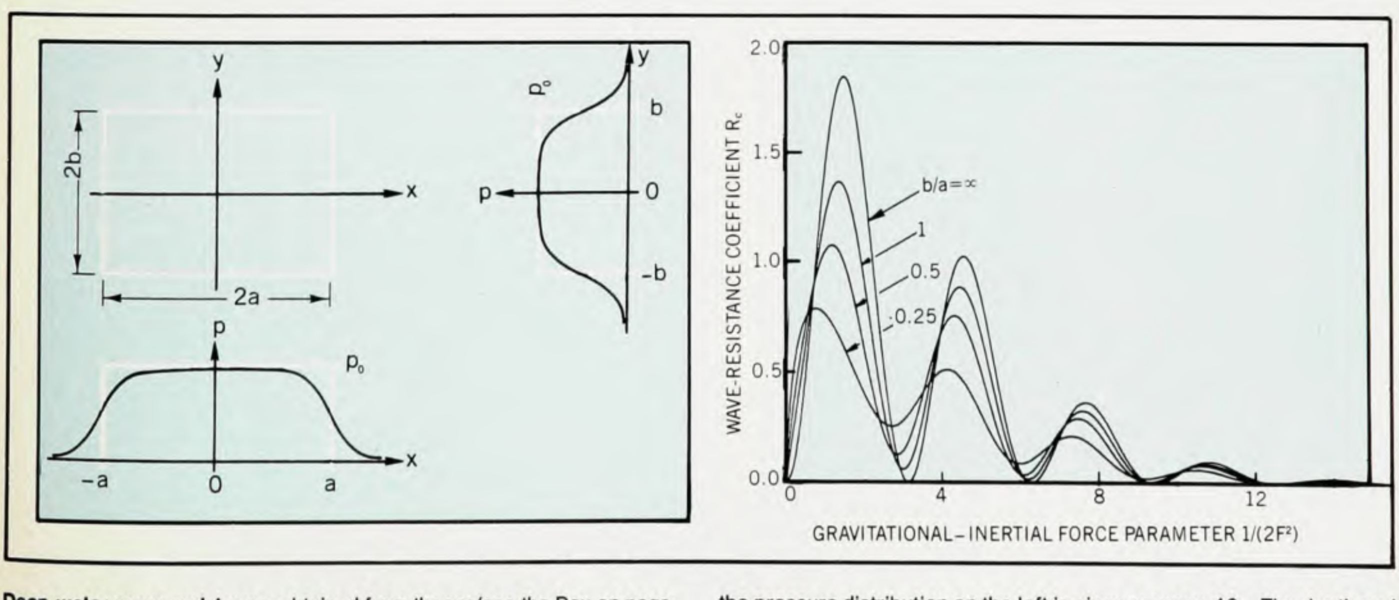
> "Any craft designed to operate for significant periods of time in the proximity of the surface over which it operates and to generate a significant part of its lift through pressurized air flow." [6]

An extensive literature is available, reflecting the many uses of this vehicle.

An air-cushion vehicle develops lift in the following way: Air is forced into a large cavity formed by the outer rim of the vehicle and the surface, ground or water. The high pressure is sufficient to lift the craft a short distance. The air cushion leaks at the periphery, but air is constantly reintroduced to compensate for this loss. The vehicle essentially floats on a carpet of pressurized air, which is continually replenished. Propulsion is achieved in a number of ways, the choice of which largely depends on the intended application: Air or water propellers, or water jets can provide the forward propulsive force.

The chief advantages of this ingenious system are very low frictional drag forces and operability over a wide variety of terrains, including land, water and ice. Previously unreachable territory is now accessible with these vehicles. The air-cushion concept has sprouted applications at all speed ranges, from the very slow to the very fast. Floating platforms have been devised to move heavy equipment for which most other means of transportation would otherwise be awkward. Flexible inflatable skirts can be fitted at the bases of large objects, easing their displacement over flat surfaces. Special trucks can be fitted with air-cushion seals to facilitate their moving over deep mud or water, thereby greatly increasing their useful range.

Important commercial developments of the hovercraft have been made, especially by the British, who have made good use of this craft over commercial routes.



Deep-water wave resistance, obtained from theory (see the Box on page 37). The abscissa is related to the Froude number F. The equation for the pressure distribution on the left is given on page 42. The depth and parameter β are infinite, and $\alpha = 5/a$. Figure 6

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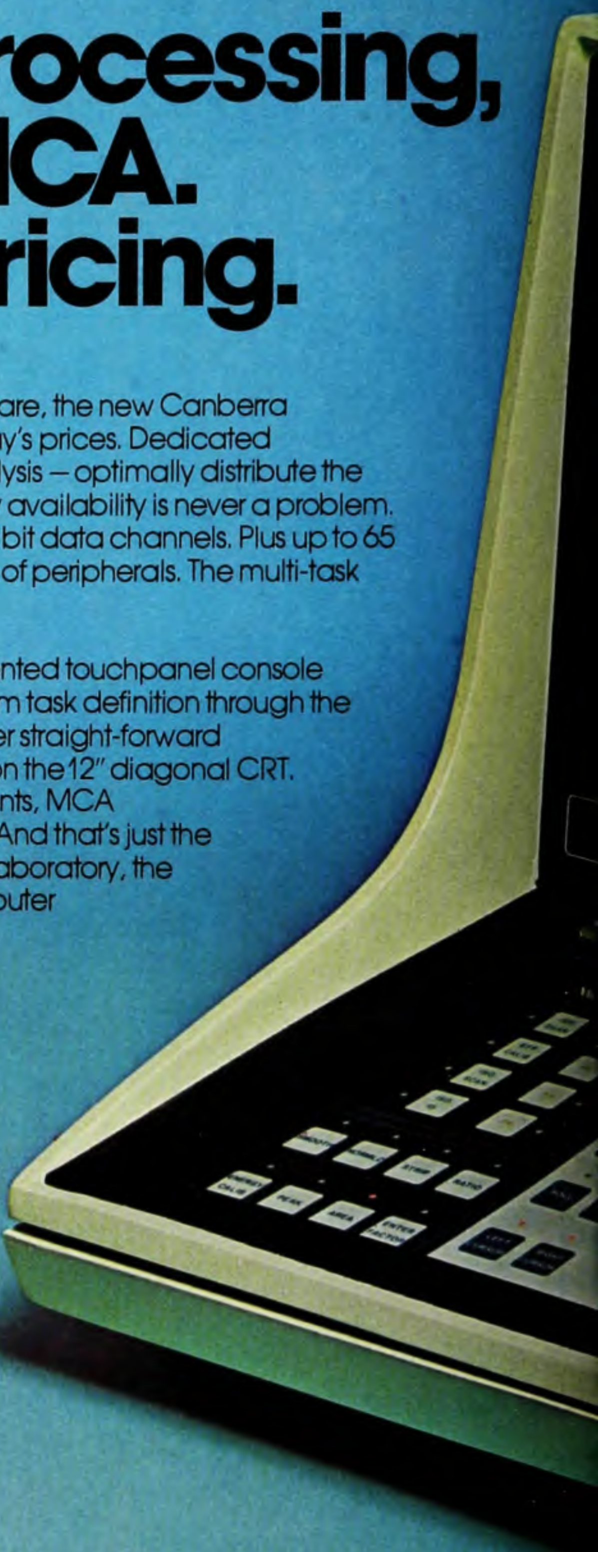

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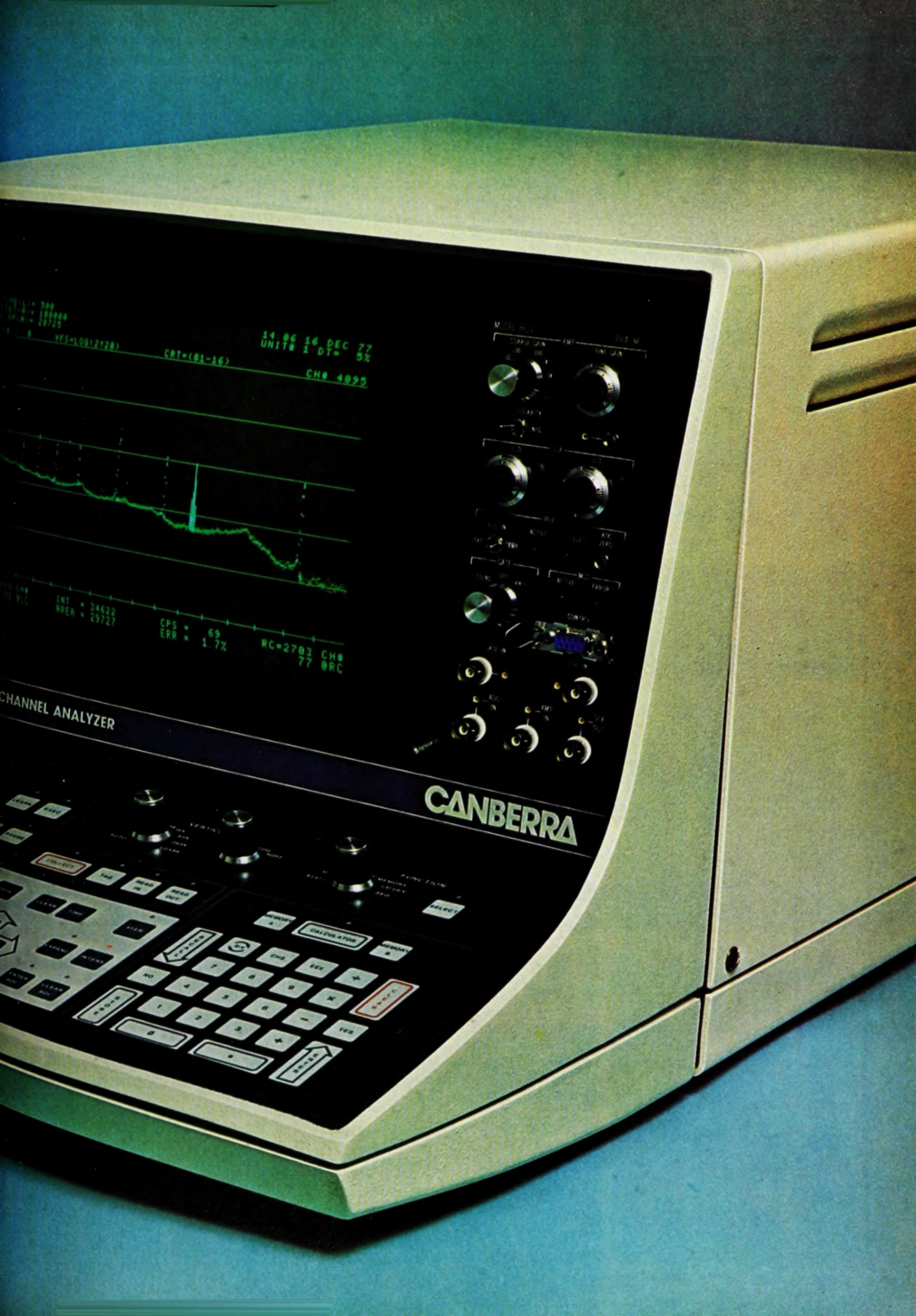
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Speeds upwards of 60 knots have been attained. Such speeds are particularly useful when large distances are to be covered. As of 1975, over 3.1 million passengers had been transported across the English Channel. The United States has also been active in the development of air-cushion vehicles. Figure 1 shows the JEFF B, designed to operate at high speeds in rough seas.

We now turn our attention to a phenomenon which, although not restricted to air-cushion vehicles, is remarkably well demonstrated by them: wave resistance. The air–water interface is capable of supporting and propagating waves, such as those produced by a ship as it perturbs the water surface on which it travels. These waves radiate away from the ship, causing a drag force as explained previously. To be sure, all surface ships are subject to wave resistance. From a theoretical point of view however, air-cushion vehicles present a "cleaner" problem because ideally no part of the craft is in actual contact with the water; this dispenses with a cumbersome boundary condition.

The model usually adopted is that of a moving pressure distribution over the water surface. This pressure, due to the air cushion generated by the craft, causes a local depression over the surface. The motion of this depression produces waves, which carry energy away from the source of disturbance. The wave-making ability of a body is, in general, a function of its shape and speed, and the water depth. Free-surface problems such as those related to wave resistance are among the most interesting research topics in ship hydrodynamics. As with most problems in fluid dynamics, the objective is to describe the fluid velocity field around a body or disturbance in the presence of a given onset flow. In free-surface flows we are faced with the additional difficulty of having to determine the surface shape as well. Analytical approaches have thus far been limited to perturbation analyses, corresponding physically to a small-pressure load that causes waves of small amplitude.[7]

This problem involves irrotational flow and therefore admits a velocity potential, which, by virtue of mass conservation, satisfies Laplace's equation. The interesting physics, however, is contained in a boundary condition at the surface which prescribes the pressure to be atmospheric everywhere except underneath the vehicle where it is given a function of cushion size and vehicle weight,

$$p(x,y) = {}^1\!/\!_4 p_0 [\tanh \alpha(x + a) - \tanh \alpha(x - a)] \times [\tanh \beta(y + b) - \tanh \beta(y - b)]$$

where p_0 is the cushion pressure, α and β are parameters, and the craft is $2a$ long by $2b$ wide.

Wave-like solutions are found, which radiate away from the vehicle. These permit the computation of the horizontal component of the force acting on the deformed surface—that is, the wave resistance. The most striking feature of these results is the strong interaction between waves generated by various parts of the air cushion. These wave systems can interfere constructively or destructively, according to the speed of the craft, the local water depth and the detailed shape of the cushion. A series of resistance maxima is therefore predicted as a function of ship speed. Figure 6 shows these results in terms of the wave-resistance coefficient

$$R_w = \frac{R\rho g a}{W p_0}$$

as a function of the reciprocal of twice the Froude number squared, where R is the wave resistance, W the weight, ρ the water density and g the gravitational acceleration. The Froude number, F, equals $V_0[2ag]^{-1/2}$, where V_0 is the craft speed. The amplitude of the various peaks is a strong function of cushion shape. This is to be expected, because the cushion acts as a distributed source for the wave field and it is the relative phases of these waves that determine the observed resistance. This research topic is unusually rich; aside from generating fascinating problems in applied mathematics, it is of immense practical concern to designers.

The questions—yet to be asked

A great deal of hydrodynamics goes into the design of present-day ships. There are, however, great gaps in our understanding of flow phenomena. Research in cavitation, ventilation, boundary layers, turbulence and other areas continues. Scaling laws that relate measurements made on reduced-scale models to full-scale applications are needed to predict performance and aid the design process. Modern ship hydrodynamics being roughly a century old, we can not claim to have answers to many of our questions. In many cases, the questions themselves have yet to be asked.

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