Script of the Film

FORM DRAG, LIFT, AND PROPULSION

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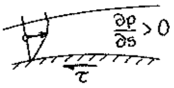
Separation at edge of plate

Animation



In our previous films, separation of flow from a boundary was treated as a purely geometric effect. A plate, or orifice diaphragm, for example, is usually too thin for the flow to follow without an impossibly low pressure at the edge; separation simply reduces the curvature of the limiting streamline till a physically possible pressure field is realized. In general, however, separation requires not only an adverse pressure gradient, as in any region of deceleration, but also a zone of already retarded flow as is produced by shear in the boundary layer.

Separation before stagnation zone

Separation at rear of cylinder

Separation below hydraulic jump

Here the central streamlines do not separate as the pressure rises toward the point of stagnation, because the flow between them is not otherwise retarded. But the fluid in contact with a splitter plate is already at rest and cannot be further decelerated, so that separation must take place if the flow is to continue. As the boundary layer develops around any body of appreciable curvature, the point of separation rapidly moves forward from the zone of maximum pressure rise at the rear to the zone where deceleration first occurs. As a matter of fact, no change in boundary alignment is really necessary, just so long as there is a shear zone of low velocity and an adverse pressure gradient, such as prevails beneath the front of this undular surge moving slowly against the flow.

Separation at expansion

Wake behind disk

Unstable flow over hinged block

Separation leads to three important occurrences. First, it changes the anticipated flow pattern; for instance, this channel expansion obviously does not cause the flow itself to expand as rapidly as desired. Second, it produces boundary drag, thereby expending energy through the generation of eddies, which rapidly transform to turbulence. Finally, it can lead to oscillation of the flow, with a corresponding pressure fluctuation, boundary vibration, noise generation, and perhaps even structural damage.

Rotating cylinders

Though separation is very essential in the operation of parachutes and baffles, it should in general be avoided by the control of the boundary layer or the pressure gradient, or of both together. If the boundary moves with the flow, for example, the retardation by shear is offset, and separation obviously is prevented. Much the same elimination of separation is realized if, as is now beginning to occur, fluid is discharged tangentially

Boundary-layer injection and withdrawal

Use of vanes in normal and mitered bends

into the boundary-layer region through boundary slots. Even better results will next be seen to obtain as the boundary layer fluid is sucked into the slots as rapidly as it is retarded. A change in the pressure field as a whole is provided by the introduction of guide vanes. These can be made to conform to the original boundary, and thus increase the relative radius of curvature locally, or else the whole structure can be redesigned accordingly, as in the case of this miter bend; the flow is obviously much worse without the vanes, but much more efficient once vanes have been installed.

Animation

$$C_D = \frac{F_D/A}{\rho V^2/2}$$

Pressure distribution on disk

Dynamometer

A type of Euler number that indicates the effect of separation is known as the drag coefficient - the longitudinal force exerted by the flow per unit projected area in its ratio to the stagnation pressure. For extreme degrees of separation, as must occur at the edges of this disk, measurement of the pressure distribution at the numbered piezometers on the front and rear faces will show the cause of the drag. As air now begins to flow from left to right, the front of the disk becomes subject to positive pressure and the rear to appreciable suction. The integral of the pressure distribution will yield the same force as that measured on such an air-tunnel dynamometer.

Drag of disk, hemisphere, and streamlined body

Bodies of equal drag

The high drag of the yellow disk can be reduced appreciably by adding a rounded front, which minimizes the curvature of the separation surface and thus somewhat alleviates the pressure reduction at the rear. Separation is almost completely eliminated by adding a well-fared tailpiece to reduce the adverse pressure gradient. Since there can be no resistance to steady irrotational flow around a body without separation, practically the only resistance now is that of shear within the boundary layer. Under optimum conditions the process called streamlining can reduce the drag some 95%. Since the resisting force varies with the projected area of a body as well as with its shape, at the same velocity this streamlined form would then produce no more resistance than a disk of less than a quarter its diameter.

Pressure distribution on sphere

Drag of sphere with laminar and turbulent boundary layers

A sphere is intermediate between poor streamlining and good streamlining. As can be seen from the distribution of pressure measured at the numbered piezometers, when flow takes place from left to right the low pressure at the rear compared with the high pressure at the front indicates that separation still occurs. As is shown by injecting smoke into the wake, the line of separation is even ahead of the midsection. Making the boundary layer turbulent prematurely by a trip wire tends to reduce the separation tendency, as is evident from the shift of the sepatation point to the rear of the midsection.

End effect in drag of plate

Compared with a body producing two-dimensional flow, like this long plate, a more nearly axisymmetric body like a square has a

Drag of parallel bars

Tandem effect

much higher wake pressure and hence a much lower drag per unit area. The drag coefficient of a square plate, therefore, is increased by cutting it into more nearly two-dimensional strips and slightly separating them. A body that is in the wake of another, being in a zone of reduced velocity, experiences a great reduction in drag, as any cyclist who has coasted along behind a truck is well aware.

House and lifting roof

House and chimney smoke

Parachute

Sky diver

These elementary principles also apply to more complicated structures such as buildings. Roofs should not be designed for only positive loading, since in high winds they are most likely to be lifted by suction due to separation than they are to be blown in. Chimneys, obviously, should not terminate within zones of separation or the smoke will fill the region behind them. This is seen to be the case almost regardless of the direction from which the wind comes. Probably the most unstreamlined body is a parachute, but obviously even this can be designed for maneuverability. Moreover, even the human body in free fall can control its turning moment about three different axes, as this skydiver clearly shows.

Lecture

The mathematical concept of circulation introduced in connection with vorticity in our second film is also useful in connection with the side thrust exerted upon certain bodies in relative motion. Defined as the line integral of the tangential component of the velocity around a closed curve, Γ represents the tendency of the fluid to circulate in one direction or another around the curve.

The circular streamlines of an irrotational vortex are all lines of constant circulation, for the velocity varies inversely and the circumference directly with the radius. Now if the velocity field of such a vortex is superposed upon the velocity field of irrotational flow around a body - say a circular cylinder - the velocity on the one side will be augmented and on the other side diminished, in proportion to the relative strength of the circulation, and the flow pattern will change accordingly. Where the velocity is increased, the pressure will be reduced, and vice versa, so that a side thrust will be exerted upon the cylinder.

Such circulation is produced in actuality through boundary-layer shear if a body is rotated. This is illustrated quite graphically by this light cylinder of paper rolling down a miniature ski jump. Because of the cross thrust that its turning produces, it deviates markedly from its normal parabolic trajectory. The same phenomenon is encountered in the deflection from its normal trajectory of a spinning baseball or tennis ball.

If a cylinder is moved without rotating, on the other hand, oscillation of the pattern will produce, through the development of circulation first in one direction and then the other, an alternation of side thrust, which is at the root of such phenomena as the singing of telephone wires in the wind, or the noise generated by this rod as it is swung through the air.

Cylinder and Kármán trail

Oscillating circular cylinder

Oscillating elliptical cylinders

Failure of suspension of unstable cylinder

Tacoma Narrows Bridge

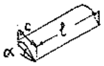
Observation of the flow pattern behind such a cylinder will reveal the alternate shedding of vortices either side of the center line, the circulation around each vortex being just the opposite of the momentary circulation around the cylinder producing the side thrust. The succession of such vortices is called the Kármán vortex trail. If the cylinder is free to oscillate under the side thrust, as it is if suspended from light springs, it will gradually develop an oscillatory motion in the transverse direction and eventually move back and forth over a distance about equal to its diameter. An elliptical cylinder with major axis in the direction of the flow will have a more limited amplitude of oscillation, whereas one with its major axis normal to the flow will oscillate much more markedly. Some asymmetric forms (like either this semicircular cylinder or ice-encrusted telephone wires) are unstable in that they will tend to oscillate farther and farther, with eventual breakage of the suspension as a result. A similar sort of instability is found in various structural sections, in particular the Tacoma Narrows Bridge here seen oscillating in a high wind prior to ultimate failure.

Starting vortex

Stopping vortex

Animation

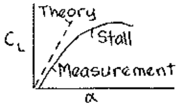
$$C_L = \frac{F_L/\ell c}{\rho V^2/2}$$



$$\sim \frac{\Gamma}{Vc} \sim \sin\alpha$$

A body that is so designed as to take maximum advantage of flow-induced cross thrust is known as a lifting vane. The circulation of the starting vortex seen here is matched by an equal and opposite lift-producing circulation around the foil. The fact that circulation actually occurs around the foil is seen from the vortices that detach as the foil is stopped. A lift coefficient can be written for a vane of length l and chord c as the lifting force per unit vane area in its ratio to the stagnation pressure. According to the circulation theory of lift, this coefficient is proportional to the relative circulation, which in turn is proportional to the sine of the angle of attack of the vane.

Animation

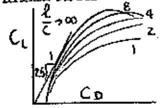


Flow pattern at stall

Pressure distribution around vane

A plot of the measured lift coefficient against angle of attack shows good agreement with the circulation theory at small angles, but a great deviation at high angles as the phenomenon known as stall occurs. By means of smoke filaments, the gradual development of stall, or leading-edge separation, is readily seen from the change in flow pattern around this symmetrical vane as its angle of attack is continuously increased. Piezometers at the numbered points around the profile of a vane show that in a steady crossflow the circulation induced with growing angle of attack produces a pressure below and a suction above the vane, the difference increasing as the angle of attack increases till stall suddenly occurs.

Animation



Plan view of tip
vortex

End view of tip
vortex

Hydrofoil boat

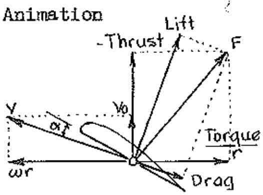
As seen from this polar diagram of lift versus drag, a well-designed lifting vane will display an efficiency, or ratio of lift to drag, as high as twenty-five or thirty. This is for an aspect ratio, length over chord, that is very great. As the aspect ratio decreases, however, the ratio of lift to drag steadily diminishes. This is because of a tip effect much like that of the shortened plate, in which flow occurs around the end and diminishes the pressure difference. Smoke filaments near the middle of a vane show only a two-dimensional separation effect. Near the end, however, as the vane is inclined first this way and then that, the pressure on one side and suction on the other give rise to an additional circulation effect, which is evidenced by an intense tip vortex. This end view of the same vane shows the growth of the tip vortex to perfection. The resulting flow directly behind the vane has a downward component, called downwash, which necessarily increases with decreasing aspect ratio. Lifting vanes are used not only for the wings of airplanes, but also under modern hydrofoil boats to lift the hulls completely out of the water, as seen on this Grumman craft being tested for the Maritime Administration. Elimination of wave resistance obviously leads to much greater speed and stability.

Airplane propeller

Successive propeller
sections

Assembly of sections

Animation



The first use of the lifting-vane principle occurred many centuries ago in connection with the windmill forerunners of the more recent airplane propeller shown here. Since each radial section of a propeller moves with a different velocity, for efficient design the blade as a whole must vary continuously in shape from tip to hub. Each successive element of the blade has the same forward speed but a tangential speed that is proportional to the radius; hence each will have a different angle of advance, and this in turn makes necessary a variable angle of the blade. For the single blade element now shown, the forward speed and the tangential speed determine its direction of motion relative to the fluid; this and the geometry of the element then control the angle of attack. The lift and drag, measured relative to the direction of motion, evidently both contribute to the axial thrust of the propeller and to the tangential force that is involved in the torque.

Ship propeller

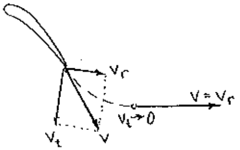
Slipstream

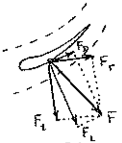
Spiral vortex

A ship propeller usually has blades of large chord so that the load is distributed over a greater area and the local pressure drop will normally not be great enough to produce cavitation. Here tests conducted under extreme conditions in a cavitation tunnel of the Navy's David Taylor Model Basin show by water-vapor formation the decrease in slipstream diameter that must always occur as the propeller accelerates the passing fluid. When the same state of flow is seen in slow motion, the tip vortex is found to yield a spiral tube of water vapor which shows the actual complexity of the slipstream.

Kaplan blades

Radial-flow unit





Encasing a propeller in a duct, as in a pump or turbine, eliminates both the tip effect and the necking down of the slipstream. The pitch of the blades is often variable from the braking limit to full feather in order to control the efficiency and other operating characteristics. Blowers, pumps, and turbines vary from the axial-flow or propeller type just shown to the radial-flow or centrifugal type like this Allis-Chalmers turbine. A radial flow unit is shown schematically in the laboratory. The stationary guide vanes give the oncoming flow a tangential component, which ideally is brought again to zero by the time the flow leaves the moving runner. The work that is done by the fluid on the runner is proportional to the change in circulation that is produced. If the camera is now rotated at the same speed to show the flow relative to its blades, these are seen to act as lifting vanes, much like those previously discussed. The components of both lift and drag evidently control the tangential force on the runner that does the useful work. However, if the rate of flow, direction of approach, and runner speed are not properly related, an effect comparable to stall will occur and the efficiency will be reduced.

Fluid coupling open
and closed

Coupling in operation

Torque converter,
reduced speed

Torque converter,
reversed output

A fluid coupling, which serves as a shock-free connection between driving and driven machinery, consists of a pump (the shaft and blades at the left) and a turbine (the shaft and blades at the right) compactly combined in a single housing. If the space is filled with a fluid of appreciable density, turning the input shaft and blades will cause the output blades and shaft to yield the same torque whether rotating or stalled, because the circulation must increase and decrease by the same amount as the fluid passes from one side to the other and back again. Inclusion of a set of stationary vanes, here shown in red, permits the circulation to be changed without doing work, so that the output vanes will yield a higher or lower torque; such a unit is called a torque converter. Proper shape of the stationary vanes will even permit the output torque to be reversed in sign.

Sectional view of
jet engine

External view of
jet engine

The general principle of using stationary guide vanes (here seen in the upper portion of this open model of an aircraft jet engine) as well as moving blades is the basis of most propulsive machinery. Though the elements are carefully shaped, and used in many successive stages, they are all basically lifting vanes. Here, however, not only the density and viscosity of the gaseous fluid must be considered, but also its compressibility - a property of which the effects will be treated in detail in the next and last film of this series.