Script of the Film

INTRODUCTION TO THE STUDY OF FLUID MOTION

by

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Lecture	The film that you are about to see has been made to show to student engineers who are just beginning their study of the mechanics of fluids as an engineering science. Such a course, if it is to be effective, must be illustrated by well-planned laboratory experiments. This would be a difficult task for even the largest institutions, if only because of the great variety of phenomena that are involved and the complexity of the equipment necessary to demonstrate them on demand. The smaller institutions are even more handicapped in this regard. When it comes to the selection of natural phenomena as examples, the use of motion pictures is the only solution for colleges both large and small. This film and those to follow are therefore intended to provide illustrative material that will effectively supplement what is normally included in a good college course.
Lecture	The ancient Greeks' classification of matter into the elements earth, water, air, and ether was surprisingly prophetic of the present-day classification of solid, liquid, gas, and plasma - the latter denoting the electrically charged particles encountered in outer space. If one include the plastic flow of the solid state, all four of these classes of matter are seen to have certain fluid properties. Usually, however, only liquids and gases are included under the fluids category. Even with this restriction, the part that true fluid motion plays in one's everyday life is astoundingly broad.
Diving Washing hands Whistle blowing Stirring coffee Swimming Smoke ring Drinking fountain Bagpiper Blood transfusion	Nearly every aspect of our work, relaxation, body care, and nourishment involves fluid flow in one way or another... Many of these actions have become so commonplace that we no longer give them even passing thought... Nevertheless, anyone who fully understood the mechanics of each elementary phenomenon that is reproduced in these familiar scenes, could truthfully claim to know more about the subject than anybody on earth... Cigarette smoke is a necessity only to some... but the water that we drink... and the air that we breath are vital to life itself. Hence they are subjects of widespread study, as is the very blood that flows in our veins.
Clouds Rain Streams	Equally important to our existence is the fluid flow involved in the hydrologic cycle of evaporation, precipitation, infiltration, and surface runoff. We take the weather as a matter of course. When it rains, most of us simply let it rain, as it has been doing for billions of years. Some of us, on the other hand, are engaged in its prediction or its recording, for such runoff as this not

Flood Blizzard	only provides us with water, transportation, and power, but during these billions of years has helped give the surface of the earth the form that it has.
Ships at sea Surf on shore Gull landing	Geologists study the flow of water, sand, and snow that they may better understand the work that has been done in ages past by rivers, winds, and waves... Meteorologists and oceanographers, of course, are interested in present-day winds and waves, in the gulf stream and other currents that exist in the ocean, and in similar prevailing air streams in the skies.
Girl diving Small fish Saw shark Porpoise Dolphin stroke	Thanks to aquatic sports, our attention has been drawn to the fact that there is almost more life below the ocean surface than above... The secret of the unbelievably low resistance that many of these natural underwater bodies possess - especially porpoises and dolphins - would be invaluable to designers of ships and planes... At the very least the dolphin has contributed the principle of this efficient racing kick.
Water skier Speed boats Pelican Gull Toy glider Private plane Jets Missile launching	This bare-footed water skier, on the other hand, has borrowed the principle of free-surface planing used in these rather more stable highspeed boats... Men like Leonardo da Vinci watched birds in flight for many years with only sketches of imaginative flying contraptions to show for it... But in the present century man has progressed with ever-increasing rapidity from toy gliders to spin-proof family planes, from formation flights like these of the Navy's famed Blue Angels to intercontinental missiles like the four-stage Scout of the National Aeronautics and Space Administration. With the satellites, aeronautics has now become astronautics, the glamor profession of engineering science.
River from air Mississippi barge Tree spraying Drilling rig Oil pump Refinery Chemistry laboratory Paper mill Sewage plant Smelter	There remain, however, countless other professions dealing with fluid motion, and upon these as much as upon outer space our civilization will long continue to depend. River barges must be built. Fruit trees must be sprayed. Oil, upon which our highly mechanized existence depends, must be sought, pumped, refined, and distributed, as in this small section of the vast complex that is the Humble Oil Company. A great variety of chemicals must be manufactured. All sorts of paper must be made, as in this Consolidated mill for fine magazine stock, now seen in slow motion. Drinking water must be purified, and sewage made harmless before being returned to our streams. And the many metals that our industry and construction require must be smelted, as in this open hearth of United States Steel.
Lecture	In order to describe such a variety of flow occurrences, to design vehicles or conduits or machines which in themselves produce fluid motion, and then to predict their effectiveness of operation, we must first agree upon a special physical terminology. Fortunately, the same terminology applies to all phases of mechanics, whether solid or fluid. While many different terms are used for even this

Board: $L,\ T,\ {M \atop F},\ \theta$	one branch of engineering science - terms like intensity of shear, momentum, and rate of doing work - and whereas just as many different units of measure could be devised, both the terms and the units are actually reducible to only three - length, time, and either mass or force - with the possible addition of temperature if we wish to include certain thermodynamic phenomena involved in high-speed flow. Any type of fluid motion can thus be described quantitatively in terms of units relating to these three or four dimensional categories.
Water jet Stream gaging Area measurement Ship sections Spraying model Slime-mold swarm cell Dracone tanker	The shape of a fluid stream can be described in terms of length alone. Whether one measures the diameter of a jet with a micrometer or the depth of a river with a staff, the principle is the same. The area of the flow passage is then determined by planimeter in terms of length squared, and the volume as length cubed... The same procedure is used to define the form of a ship hull... whether a prototype... or a model such as this. Scale is a very important factor in fluid mechanics, for the size of a boundary is as important as its shape. This microscopic cell, for example, is less than one millionth as large as this flexible British oil barge of similar form.
Water clock Timing swimmers Hot-wire anemometer Revolution counter Hurricane plot Sun flare	Time, the second fundamental dimension, was once measured appropriately by water clocks such as this replica of an Egyptian clepsydra which marked fractions of a day 3000 years ago, but we know it most intimately as it is indicated by a watch in hours, minutes, or seconds. Some flow occurrences take place so rapidly that electronic means of splitting seconds into a thousand or even a million parts must be employed. On the other hand, such natural phenomena as floods or hurricanes require days to advance across the earth, and cycles of solar activity are reckoned at Mount Palomar in years.
Wave timer Midget propeller Airport anemometer Current meter Channel contraction Vortex Satellite photo Nebula	The combination of length and time serves to define such terms as speed and rate of flow. Speed, which signifies distance traversed per unit time, is measured by propellers, anemometers, and current meters such as these. Velocity is a combination of speed and direction, each of which is seen from a pattern of particles carried by the flow. Acceleration, or velocity change per unit time, is also represented by the changing flow pattern. Both length and time scales are involved in comparing small and large patterns. This vortex in a small tank is basically similar to the vast cloud formations of very small rotational speed observed from a Weather Bureau satellite. Both have much in common with the tremendous spiral nebulae in remote parts of space as photographed at Palomar.
Equations: $F = Ma$ $W = Mg$ Centrifuge	Force and mass, one or the other of which is the third fundamental dimension, are related through the Newtonian equation. However, they are often confused, largely because a particular type of force - the weight of a body or the attraction of gravity upon it - is, here on earth, an almost constant multiple of its mass. One could measure mass with a centifuge through use of the Newtonian

Weighing tank
Spring balance
Ball accelerated
Pycnometer

equation, accelerations thousands of times that of gravity being obtainable... Usually, however, we measure mass indirectly on a beam balance by comparing the weight of the body in question with that of a standard body, both under the same gravitational conditions. But a spring balance measures absolute force and would hence indicate a zero weight for a body out in space or immersed in a liquid of equal density. Mass acceleration, however, photographed in slow motion, requires force even when the mass is weightless... Mass density and specific weight are determined by measuring the mass or weight of a known quantity of a substance - contained, for example, in a calibrated pycnometric flask.

Barometer
Weather map
Blood pressure
Hydraulic lift
Drinking with straw
Collapsing can
Vacuum pump

Fluid pressure has the dimension of force per unit area. We are familiar with barometric pressure, the force exerted by a column of the atmosphere on a unit area of the earth's surface, and its relation to the highs and lows of a weather map. Blood pressure as an indication of physical well-being is also a common concept of our everyday life, as is the hydrostatic multiplication of force in various forms of the hydraulic press and hydraulic lift. Pressures below atmospheric - the principle of any siphon - are measures of a partial vacuum... The ancient Greeks said that Nature abhors a vacuum, but even with commercial machinery man is able to remove a surprisingly large percentage of the air from containers ... With mercury vacuum pumps he is approaching the complete void of outer space.

Bubble in oil
Draining car
Pouring of liquids
Tipping plate glass
Smoke clouds
Smoke plume in air
Sediment in water
Air bubbles

The tangential force known as shear, which resists fluid deformation, is due to the property called viscosity. We are aware of this property primarily in connection with automobile lubricants, different grades being purchased for cold and warm seasons... Liquids can become extremely viscous, like cold honey, here compared with water, which is viscous to a far lesser degree. As seen from this sheet of glass falling on another sheet without breaking, the cushion of air between them is also viscous. Air is actually fifteen times as viscous as water and hence fifteen times as stable against the onset of turbulence. But once turbulence begins - whether in a plume of rising smoke... or a plume of falling silt - viscous shear occurs in every eddy, large and small, and the effort required to maintain the flow increases greatly.

Equation:

$$E = \frac{\Delta p}{\Delta \rho / \rho}$$

Launch
Fathometer
Depth chart
Water hammer

Another fluid property of importance is elasticity - the ratio of applied pressure to the relative change in density that it produces. Though usually considered incompressible, liquids are sufficiently elastic to permit submarine signaling and sounding by the generation and reflection of elastic waves, as in this Corps of Engineers Mississippi River measurement of channel topography... When a valve is suddenly closed, elastic waves also cause the noisy plumbing phenomenon known as water hammer. The compressibility or elasticity of gases is represented by the equation of state of thermodynamics, Equations:

$$\frac{p}{\rho\theta} = \frac{pv}{\theta} = \frac{49,600}{m}$$

Air compression

in which p, ρ, and θ are the pressure, density, and temperature already discussed, v is alternatively the volume per unit mass, and m is the molecular weight of the gas. The changes that you see going on as this cylinder of air is compressed and allowed to expand are in accordance with this law. Note the temperature "creep" due to heat conduction.

Lecture

Our object in studying fluid motion is to gain an understanding of the mechanical principles that it involves so that this knowledge can be used in engineering design and control of natural and man-made phenomena. The detailed aspects of these principles will be illustrated in subsequent films, and in your classes you will learn how to apply the principles individually and - where possible - in combination. For the moment let us consider the many problems which are so complex that their analytical solution is still impossible. It is in permitting the empirical solution of such problems that the scale model proves its worth. A great many laboratories, usually federal, exist throughout the country to conduct model tests of various sorts before prototype structures involving fluid motion are designed or built.

Board:

L, V, F, ρ

$$\mathbb{E} = \frac{F/L^2}{\rho V^2} = \text{const.}$$

Model similitude, of course, is also based upon scientific principles, simple as they may be. One of these states that if a given case of flow involves only the geometric scale, the relative velocity, the force of the flow on a boundary, and the fluid density, then the dimensionless ratio of these four characteristics must have a constant magnitude. The ratio is often called the Euler number. Two geometrically similar cases of such flow would then always be dynamically similar, regardless of scale and fluid, because their Euler numbers would necessarily be the same.

Prototype parachute

Model parachute

Almost any unstreamlined device moving completely submerged is one for which the Euler number is essentially constant. A parachute is a perfect example; in fact, the motion of this very large naval one in air is so well simulated at reduced scale in a water tunnel of the Navy's David Taylor Model Basin at Carderock that model opening time and drag are directly convertible to field conditions.

Equations:

$$\mathbb{F} = \frac{V}{\sqrt{gL}}$$

$$\mathbb{E} = f(\mathbb{F})$$

Grand Coulee

Friant jets

Flip bucket

Prototype breakwater

Model breakwater

If gravity is also involved, an additional ratio, called the Froude number, would exist; the Euler numbers, which would then depend on the Froude numbers, could be the same only if they too were the same; evidently, if two geometrically similar flows were to be dynamically similar, the velocities would have to vary directly with the square root of the lengths. Though overflow structures like Grand Coulee Dam of the Bureau of Reclamation are dynamically similar if geometrically similar, jet effects, such as those at the Bureau's Friant Dam, or in this model flip bucket at its Denver laboratory, definitely do depend upon the Froude number. The same is true of wave forces on breakwaters, photographed here by the Corps of Engineers in Hawaii, and here modeled in the Corps' Waterways Experiment Station at Vicksburg... One complexity that obviously cannot be modeled is the formation of spray.

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Equations:
$$R = \frac{VL}{\nu}$$
$$E = f(R)$$
Model plane assembly
Model in spin tunnel
Tilting-wing model
Tilting-wing prototype

If, instead of gravity, the viscosity were involved, ratios known as Reynolds numbers would control the Euler numbers, and the velocity should then vary inversely with the length. The Reynolds number becomes the criterion of similarity in the motion of submerged streamlined bodies like submarines and airplanes... This model plane is being assembled in a Langley Field shop of the National Aeronautics and Space Administration for observation in a spin tunnel, and here a vertical-takeoff model is being tested by the NASA in a regular wind tunnel; the results in either case are directly convertible to prototype scale through constancy of the Reynolds and Euler numbers.

Prototype ship
Cutting model
Scraping
Polishing
Towing-tank test
Polaris launching

Ships that move on the water surface involve both wave resistance and viscous resistance to their motion - and hence for similarity require that both the Froude and the Reynolds numbers remain the same. This is physically impossible at reduced scale if the same fluid is used, as will be true of this model now under construction, and hence the Froude criterion is followed and the Reynolds-number effect introduced later by computation... These successive steps in the preparation of a small-scale model at the David Taylor Model Basin culminate in its suspension from the carriage of the towing tank for tests under severe wave conditions, as photographed in slow motion. Obviously, modeling a phenomenon so complex as the submarine launching of a Navy Polaris could be accomplished only by breaking the phenomenon up into a number of parts to be simulated separately.

Prototype river
Model from plane
Model from ground

This air view of the confluence of the Arkansas and Mississippi Rivers illustrates another class of flow problems involving both gravitational and viscous aspects. If such rivers were reproduced at a scale small enough to include all parts of interest - as in the Waterways Experiment Station's Clinton model of the Mississippi system - the depth would be a small fraction of an inch. Instead, the model is built with exaggerated depth, roughened artificially until it will reproduce past records, then assumed to be capable of indicating the future.

Equations:
$$M = \frac{V}{\sqrt{E/\rho}} = \frac{V}{c}$$
$$E = f(M)$$
Supersonic plane
Supersonic tunnel
Sound-wave patterns

If it is the fluid elasticity that is important, the essential ratio takes the form of a Mach number - the denominator of which, it should be noted, is the speed of sound. The Mach number now controls both the Euler number and the condition of similarity. Flow in which the elasticity or compressibility is a factor is well represented by today's supersonic planes such as this NASA experimental craft. In a supersonic wind tunnel of the NASA at Langley Field, the sound waves which these planes produce, and which retard their flight as water waves retard a ship, are observed by the Schlieren process as the Mach number rises.

Lecture

You have just been shown a hundred different scenes protraying typical instances of fluid motion taken from various aspects of civilized life. As many more could have been based upon such equally important matters as heating and ventilating, irrigation, ballistics, drainage, lubrication, placer mining, hydroelectric power, combustion, groundwater control, smoke abatement, and so on and on. Today, moreover, the horizons of engineering science are advancing at least as rapidly as civilization itself. Student engineers thus have the double task of learning to apply principles that are already known and preparing themselves to assimilate those that are still to be discovered during their professional lives. The mechanics of fluids is as characteristic of present-day trends as an engineering science could possibly be.