

The Water Tunnel as a Tool in Hydraulic Research

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INTRODUCTION

The expanding scope of application of the water tunnel is largely the result of war research needs. Since the first known elementary water tunnel was used by Parsons in England in 1898 to investigate propellers, its application has remained primarily in the field of ship propeller testing. Meanwhile, investigations of other submerged bodies and of most fundamental phenomena in fluid dynamics have been performed in the many wind tunnels throughout the world. Even the broad development in hydraulic laboratory techniques that accompanied the revival of interest in scientific hydraulic research during the last twenty-five years did not emphasize the water tunnel as a general tool. In the early stages of World War II, however, there was a shortage of equipment in America, and apparently also abroad, to supply information for underwater ballistics design. Additional facilities in which flow could be produced with cavitation, as well as without, were needed, and these preferably of a type suitable to more general application than the existing propeller tunnels.

As a result, there exists now, in addition to propeller testing tunnels, a limited number of water tunnels whose prime purpose is the investigation of flow about bodies in general. Two of these are in the United States, one at the University of Iowa, and one at the California Institute of Technology. This new practice with its additional techniques extends the role the water tunnel is destined to play in hydraulic research. Thus in the current period of reconversion, which applies to research objectives as well as production objectives, a discussion of the present development of water-tunnel equipment and the possible scope of its application in peacetime is appropriate.

WATER-TUNNEL APPARATUS AND RESEARCH TECHNIQUES

Comparison of Water and Wind Tunnels

As with wind tunnels, two water-tunnel arrangements are possible: the open-circuit type and the closed-circuit, or return-flow, type. Practically, only the return-flow type, where pumps or propellers are used to circulate the flow through a closed loop, is important. Open circuits are practical only where large volumes of water under suitable head can be circulated through the device and wasted. The simplicity associated with the open-circuit wind tunnel, where air is drawn from the atmosphere and returned to the atmosphere, is difficult to duplicate for the water tunnel.

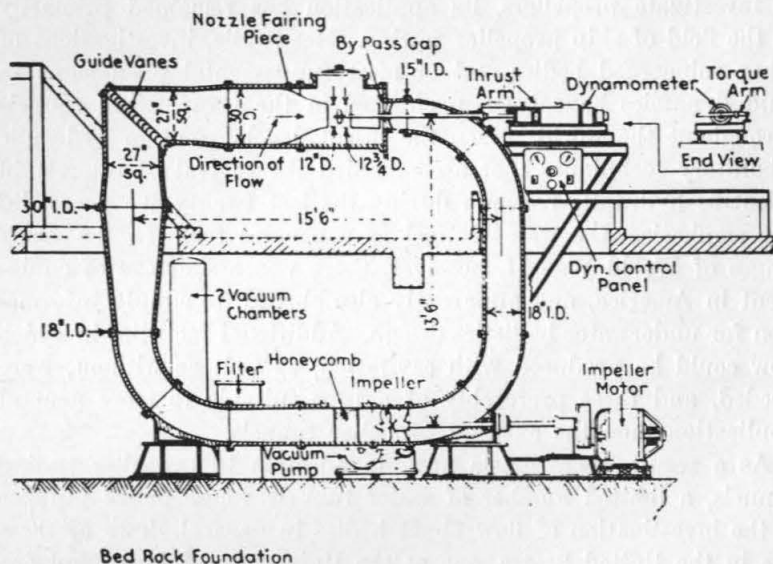


FIG. 1—12" PROPELLER TESTING WATER TUNNEL AT THE DAVID W. TAYLOR MODEL BASIN.

Water-tunnel working sections, again like wind tunnels, can be of the "open jet" type or "closed jet" type. In the "open jet" type a jet discharges submerged into a water-filled chamber whose dimensions normal to the jet axis are somewhat larger than the

jet thickness. After traveling a certain distance submerged, the jet water enters a "gathering" nozzle and is conducted away. The body under test is supported in the jet. This arrangement is designed to give a constant static pressure over the length of the

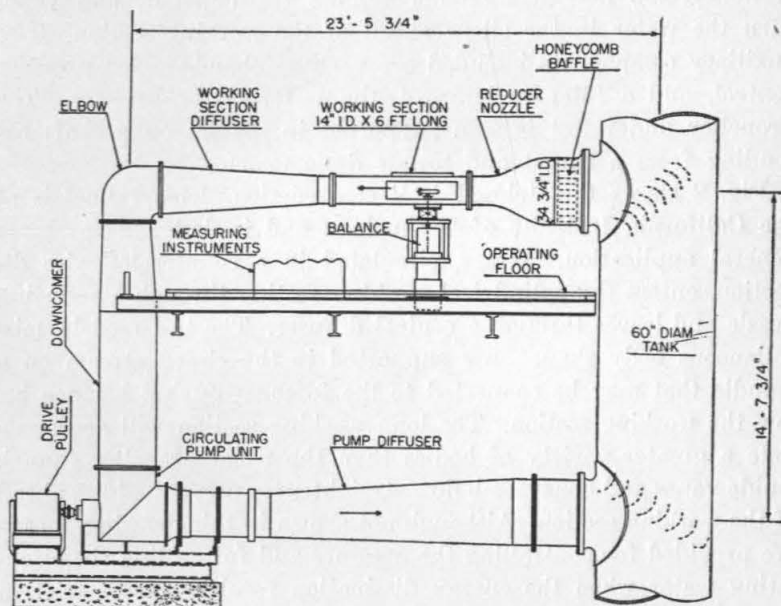


FIG. 2—14" HIGH-SPEED WATER TUNNEL AT THE CALIFORNIA INSTITUTE OF TECHNOLOGY.

working section. By contrast, in the "closed jet" type the water merely flows through a tube of rectangular or circular cross section. The test body is again supported in the stream. This arrangement provides steadier flow conditions, but with an appreciable pressure drop in the direction of motion.

General Features of Typical Water Tunnels

Figs. 1 and 2 show two examples of closed-circuit water tunnels. Fig. 1 is a propeller testing tunnel at David Taylor Model Basin [1] which employs an "open jet" type working section. Water circulated in a clockwise direction by the impeller at the bottom of the loop approaches the working section at low velocity. It is

accelerated in a nozzle and discharges as a submerged jet into the working section chamber. After traversing the length of the chamber the jet enters an expanding nozzle followed by an expanding elbow. The water velocity is low again at the circulating impeller. A honeycomb flow straightener follows the impeller, and vanes turn the water in the elbow ahead of the working section. Two auxiliary components included are vacuum chambers for pressure control, and a filter to improve the water's transparency. The propeller under test is seen supported in the jet on a shaft extending from a thrust and torque dynamometer.

Fig. 2 shows the "closed jet" construction. This tunnel is at the California Institute of Technology and is designed for more general application. Water, circulated in a counterclockwise direction, enters the cylindrical working section through a reducing nozzle and leaves through a conical diffuser. The test models, miscellaneous body shapes, are supported in the closed stream on a spindle that may be connected to the force-measuring balance below the working section. The long working section will accommodate a greater variety of bodies than the usual propeller tunnel. Guide vanes and honeycomb flow straighteners prevent eddies ahead of the working section. Although not shown in this drawing, means are provided for controlling the pressure and for cooling the circulating water when the energy dissipation resulting from friction loss exceeds the radiation rate.

Basic Requirements of the Water-Tunnel Flow Circuit

Basically, the water tunnel is a device for simulating the conditions of relative motion obtained when free bodies move in an infinite body of fluid. As developed to date it is used almost exclusively under steady flow conditions. Several requirements of the flow circuit then follow. First, a uniform velocity distribution is necessary throughout the working section space to be occupied by the model. Second, provision must be made for maintaining steady flow in the working section and, while not absolutely necessary, means of varying the flow velocity is a practical essential. Third, of course, some means must be provided for supporting the test model in place in such a manner that the support offers a minimum of "interference" to the flow about the body. Fourth, the feature that distinguishes the water tunnel from the ordinary

flume, and makes possible the most important applications, is the provision for controlling the pressure in the working section.

The method of obtaining a uniform velocity distribution in the working section is essentially the same for all tunnels. First an effort is made to assure a flow free from eddies in the approach section to the nozzle. As already illustrated in Figs. 1 and 2, turning vanes are used in the elbows of the circuit and honeycomb flow

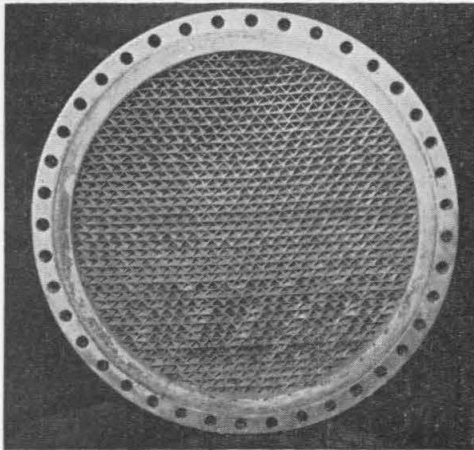


FIG. 3—TYPICAL FLOW STRAIGHTENING "HONEYCOMB". THE TRIANGULAR OPENINGS ARE ABOUT 1" ON A SIDE AND THE LENGTH OF PASSAGE IS 12".

straightening vanes (Fig. 3) follow the pump and precede the working section [2], [3], [4]. Second, the flow is accelerated just before it enters the working space. This produces a uniform axial velocity profile, such as the example in Fig. 4, and tends to minimize the effect of possible turbulent eddies or flow angularities that do exist [5], [6].

Steady flow in the working section requires that complete stability of the flow in the water-tunnel circuit and within the circulating pump or propeller be met jointly. First, then, the circuit design must eliminate possible causes of unsteady conditions such as zones of eddy formation in the nozzles, diffusers, and elbows. Design of these items requires careful consideration of effects of turbulence, boundary layer growth, and even cavitation on flow separation. Actually, purely as a result of such instabilities, most tunnels are

operated under conditions deemed "satisfactory", but which, in truth, do not give *steady* flow. Second, the pump must have a stable characteristic. Since this is obtained readily for pumps operating on a straight friction-loss load such as obtained in the water tunnel, constant flow velocity can be maintained if the pump speed is without fluctuations. The synchronous motor is the simplest source of steady speed, but limits operation to a single flow velocity unless a variable-frequency source is available or the pump is of the adjustable-pitch-propeller or the adjustable-guide-vane type. In

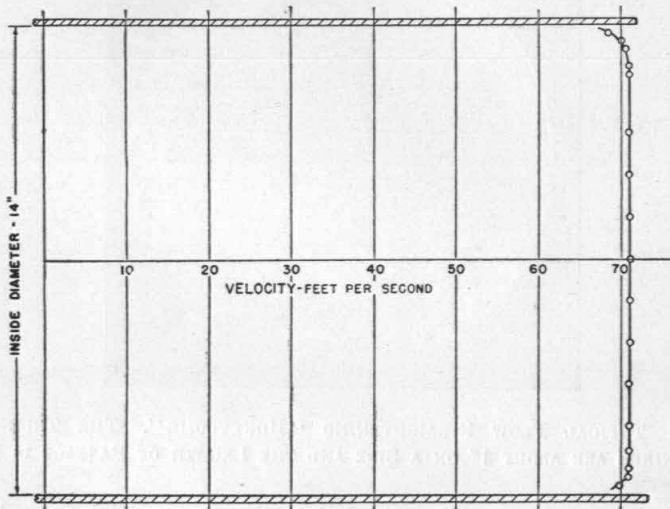


FIG. 4—TYPICAL PROFILE OF AXIAL VELOCITIES FOLLOWING A NOZZLE WITH A 6.2 TO 1 AREA RATIO.

practice, internal-combustion engines and various alternating- and direct-current electrical motor arrangements are used to obtain a range of speeds and flow velocities. Usually no special provisions are incorporated to *control* the speed, even though it is generally recognized that high accuracy requires some self-compensating speed control devices. Hydraulic governors for engines and various voltage- and field-current control devices for electric motors will maintain constant speed within relatively narrow tolerances. Cur-

rent or voltage control regulated by comparison with an oscillating quartz crystal or tuning fork will hold a motor speed to an accuracy of one tenth of one percent [7].

The provision for supporting the test model depends on the kind of model and the kind of information required. The axial shaft required for propellers is also useful for measuring the drag (thrust) on some other types of bodies. This arrangement is not satisfactory for all cases, because the spindle interferes with the flow in the wake of the body. When more than one component of the hydrodynamic forces are to be measured the model is usually supported from the side or bottom by struts or wires brought in normal to the flow. In order that the flow about the free body be reproduced as faithfully as possible all supports must be "streamlined" or surrounded by streamlined shields so as to disturb the flow as little as possible. An example of a streamlined support is shown in Fig. 5.

The water tunnel is well suited to tests of two-dimensional as well as three-dimensional bodies. With test units that span the working section from wall to wall the separate supporting strut is eliminated.

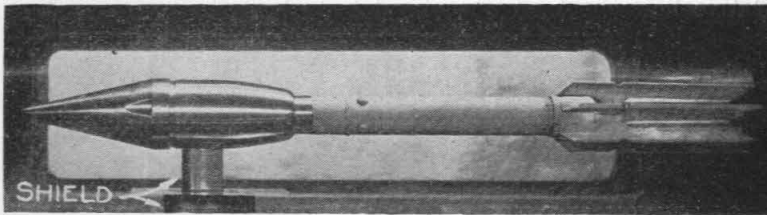


FIG. 5—TEST INSTALLATION SHOWING STREAMLINED SHIELD AROUND MODEL SUPPORT. THE CHANGE IN SHIELD DIMENSIONS CORRESPONDS TO A REDUCTION IN DIAMETER OF SUPPORT. HORIZONTAL PLATE PREVENTS LATERAL CROSS FLOWS AT JUNCTION. (FLOW LEFT TO RIGHT.)

A system for regulating the tunnel pressure is necessary for cavitation investigations, but it is also important for experiments without cavitation. For example, in cases where a small tunnel model is to be tested at the prototype Reynolds number, relative velocities higher than for the prototype are usually necessary. This may require the static pressure in the flow to be increased above that encountered by the prototype, if cavitation is to be avoided.

Any method of pressure control involves interposing some form of pressure increaser or reducer between the atmosphere and the tunnel circuit. Hydrostatic columns, centrifugal pumps, and vacuum pumps will provide a continuous pressure variation, and are employed in various combination in existing tunnels [1], [7], [8]. In order to assure quick response to control changes in any hydraulic system it is necessary that the volume of water in the system circuit remain constant. Removal or addition of water, such as is necessary if control is by changing the water level in a constant-head tank or in an equalizer, requires a definite length of time and an undesirable lag in response. Best results are obtained if the system is completely filled with water at all times.

The prerequisite to installing any pressure regulating system is a steady flow in the main tunnel circuit. Except for certain controlled accelerations or decelerations, pressure variation caused by non-steady flow is not readily eliminated by an auxiliary regulating system.

Additional Requirements for Cavitation Tunnels

Satisfying the requirements for faithful reproduction of the relative flow about an unconfined body leads to two special con-

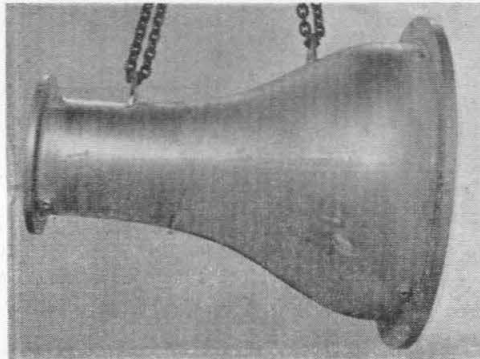


FIG. 6—NOZZLE IN WHICH THE PRESSURE ALONG THE WALL DROPS CONTINUOUSLY IN DIRECTION OF FLOW.

siderations when working with cavitation. One is the importance of making certain that cavitation occurs on the test model before it appears at any other point in the tunnel. The other is the desirability of controlling the amount of dissolved air in the water.

Accidental cavitation in any of the circuit components will result in unsteady flow conditions, while cavitation in the entrance nozzle or on the supporting strut will interfere directly with the flow about the model. Furthermore, advanced cavitation in either the diffuser following the working section or in the circulating pump will put a limit on the range of pressure and velocity obtainable in the working section.

Nozzle cavitation can be eliminated if the pressure along the nozzle wall drops continuously in the direction of flow, so that the

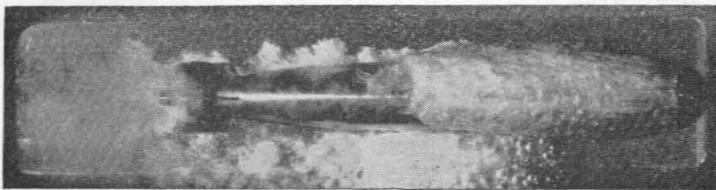


FIG. 7—ADVANCED CAVITATION ON STREAMLINED BODY. NOTE SEVERE CAVITATION ON SUPPORT. WHITE SPECKS THROUGHOUT FLOW ARE BUBBLES OF RELEASED AIR RE-CIRCULATING THROUGH TUNNEL. (FLOW RIGHT TO LEFT.)

maximum velocity and lowest pressure both occur at the throat [9]. The example in Fig. 6 shows the proportions obtained for a 6.2 to 1 area reduction. The absence of adverse pressure gradients also eliminates the possibility of flow separation for pressure ranges where cavitation is not a problem.

A similarly satisfactory design is needed for diffusers where cavitation originates in vortices formed when the flow separates from the diffuser wall. It is essential here to postpone separation until a large degree of pressure recovery is effected, an accomplishment that is difficult in the presence of an adverse pressure gradient.

Any pump or propeller whose size is reasonably well fitted to the desired circulating rate will cavitate before most of the tunnel test models unless it is placed lower than the working section. Where extreme cavitation is to be produced in the working section a very large elevation difference may be necessary if pump cavitation is not to be a limiting factor in the tests.

Cavitation will occur on a two-dimensional body sooner than on a body of revolution having the same profile in longitudinal cross-section. Thus, unless the support shield profile is very long relative

to its thickness, cavitation will occur there before it appears on the better models. Fortunately, the same refinement is not necessary for all applications. Fig. 7 shows, for example, advanced cavitation on a streamlined test body. Under the test conditions the shield also cavitates severely and offers serious interference to the flow. On the other hand, Fig. 8 shows that with a blunt body advanced cavitation can be produced before cavitation on the shield becomes excessive.



FIG. 8—CAVITATION ON A SQUARE END CYLINDER WITH AXIS PARALLEL TO FLOW. NOTE SLIGHT CAVITATION ON SUPPORT. (FLOW LEFT TO RIGHT.)

As already mentioned, the separate support can be eliminated for two-dimensional tests. The resulting simplicity is shown in Fig. 9 by the photograph of cavitation on a cylinder spanning the full diameter of the working section. In the figure the upper photograph shows an end view of the cylinder and the resulting "two-dimensional" cavity.

The dissolved air and other gases normally present in the circulating water are gradually released with a lowering of the tunnel pressure. Thus, under some conditions, "cavitation" bubbles may appear at higher pressures or lower velocities than would be the case if the water were air free and the "cavities" contained only water vapor instead of a mixture of air and vapor [10]. If the rate of release of air is high enough, the air may not re-dissolve, but rather accumulate and recirculate with the water through the working section. An example of the undesirable result is shown in Fig. 7. Without air-content control, measurements may show appreciable inconsistencies. While techniques which rely on the assumption by the water of an equilibrium state of saturation after operating for some time at a given pressure have produced surprisingly consistent results, cavitation research has reached the

place where more positive control is needed. A basic investigation of cavitation phenomena should include ultimately experiments with water deaerated to the point that the effects of dissolved gases are completely negligible.

Instrumentation and Experimental Techniques as Affected by Applications

After providing for the reproduction of "free stream" flow conditions, actual use of the tunnel depends on the instrumentation, and the instruments, in turn, depend on the desired application.

One of the most important possibilities, the measurement of the hydrodynamic forces and moments acting on a body supported in the fluid stream, requires a "balance" that will accurately resolve these forces and moments into the desired components and

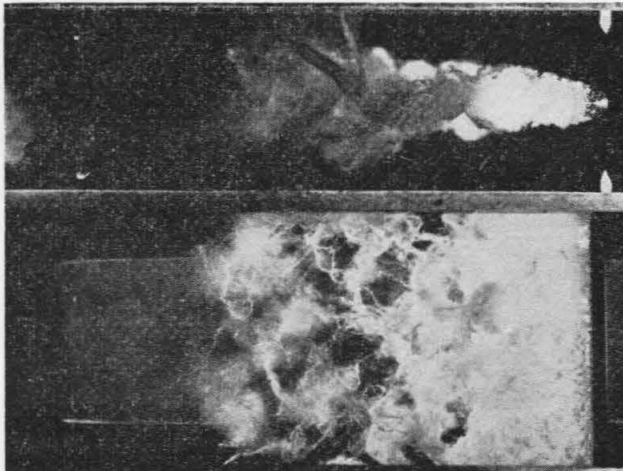


FIG. 9—CAVITATION ON A CIRCULAR CYLINDER CROSSWISE TO FLOW. END VIEW IN UPPER PHOTOGRAPH, SIDE VIEW IN LOWER. (FLOW RIGHT TO LEFT.)

will transmit them without error to some measuring system. In suspending or "balancing" a model in the tunnel the use of a "rigid" support is advantageous. In this type the test model is fixed to one or more beams which extend through the tunnel wall. These beams, or spindles, are restrained from moving under the action of the hydrodynamic forces on the model by externally

applied forces and couples. By orienting these restraining forces and couples so they act parallel to or about three mutually perpendicular axes, they can be made to correspond to any desired components of the hydrodynamic force system acting on the model.

The rigid beam has the advantage over wire suspensions in that it will take compression as well as tension, so that a counter weight system is unnecessary. In addition, orientation of the test model is fixed more accurately both because elastic deflections are less and because a balance of forces can be effected with less allowable motion of the model.

For many of the construction details of the water-tunnel balance it is possible to borrow from wind-tunnel practice. However, the special requirements of the water tunnel introduce some extra complications. The most obvious of these is the necessity for a liquid seal where the supporting spindles pass through the tunnel wall. This seal should not interfere with the spindle motion over the slight range necessary during balancing. It is possible, of course,

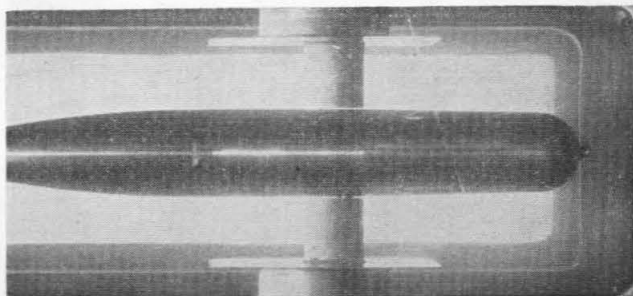


FIG. 10—TEST INSTALLATION SHOWING IMAGE OF SUPPORT SYSTEM. (FLOW RIGHT TO LEFT.)

to submerge the entire balancing system and eliminate the seal, but with water this poses other undesirable problems.

Because of the greater fluid density, the absolute magnitudes of the forces on a given size model generally are higher in the water tunnel than in the wind tunnel. This necessitates larger supporting members and shields which, in turn, cause more interference with the flow around the model. An attempt to minimize this effect is shown by the example in Fig. 5. The single supporting "spindle"

of the Cal-Tech three-component balance is made with a large diameter to within a short distance of the model, where its size is reduced. This stepped spindle is surrounded by a shield consisting

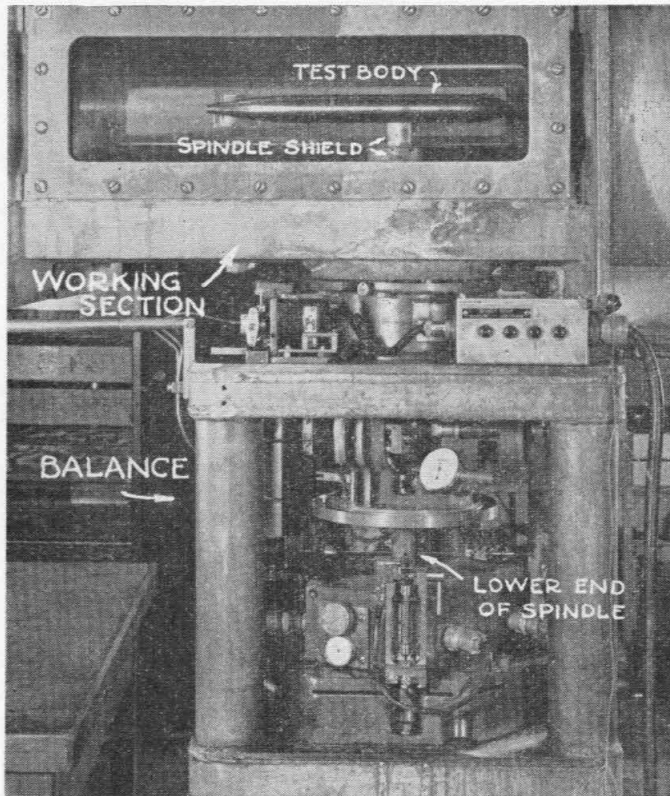


FIG. 11—CAL-TECH THREE-COMPONENT BALANCE MOUNTED BELOW WORKING SECTION. BALANCE "SPINDLE" EXTENDS UP VERTICALLY THROUGH TUNNEL WALL TO SUPPORT TEST BODY.

of two parts, a large streamlined section below and a smaller one above, with a plate between to prevent cross flow at the junction. The effects of interference and asymmetry of the flow, also caused by the supports, necessitate a correction. As for wind-tunnel work, it is the practice to approximate the true correction by obtaining measurements with and without an "image" of the support system. Fig. 10 shows a model installed with the image shield in place.

Reliable measurements require a considerable degree of refinement of the balance apparatus. This is true whether measurements are to be made of one or all six components of the forces. For good accuracy it is necessary to have a sensitivity of a fraction of a pound in the measured forces. For example, the drag of a 2-inch model of a well designed body at 70 feet per second may be of the order of 10 pounds. Two percent of this is only 0.20 pound. At 35 feet per second these figures are reduced by a factor of four.

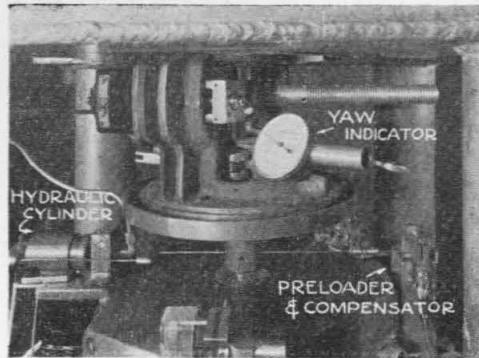


FIG. 12—CLOSEUP SHOWING FORCE-TRANSMITTING WIRES CONNECTING BALANCE SPINDLE WITH HYDRAULIC CYLINDERS AND SPRING COMPENSATORS.

Figs. 11 and 12 show the complexity resulting from an effort to measure these small forces with the Cal-Tech three-component balance. Here the spindle is supported near its center with a universal pivot that permits rotation in any direction about the pivot point but allows no translation. The hydrodynamic forces on the model are restrained by forces applied to prevent rotation of the spindle. Fig. 12 shows how a wire connection from the balance spindle to a piston in a ground and lapped cylinder converts the restraining forces to pressures for measurement with special pressure gages. While spindle motion during measurements is very small, compensation is provided for the restoring moments due to elastic deflections of the rubber seal used here and for the special wire support for the spindle. The compensators are spring "pre-loaders" with a linkage arrangement that maintains the restraining forces constant and equal to the hydrodynamic forces as the spindle moves. Fig. 13 shows one of the pressure gages. This is

a fluid-pressure scales type designed with a sensitivity of 0.01 pound per square inch. The small auxiliary gage on the front of the instrument is for rough indication of the pressure range. The overall sensitivity of the balance and gage system depends on the various piston sizes. In this case a two-to-one increase is used, so that a force of 0.005 pound on the test model causes a gage reading of 0.01 pound per square inch.

One of the special applications of the water tunnel that has proven of exceptional value is the measurement of distribution of pressures over submerged bodies. This requires special models with provision for carrying a multitude of pressure connections to the outside of the tunnel, and it reopens the question of design of support for the model. Since it is not the practice to measure forces simultaneously, the problem is less complicated than for the

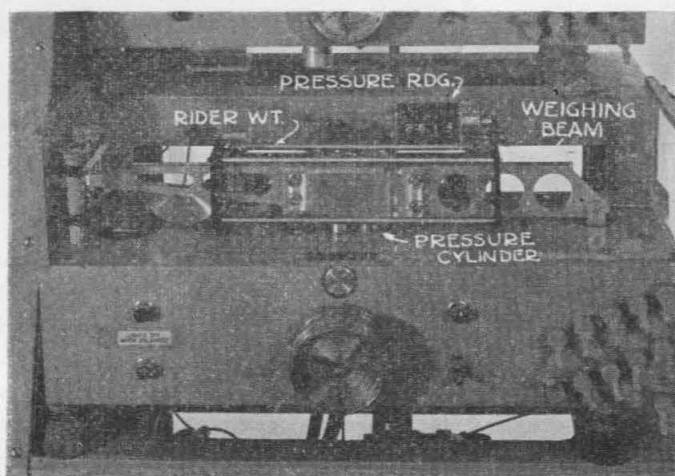


FIG. 13—WEIGHING-TYPE PRESSURE GAGE USED TO MEASURE HYDRAULICALLY TRANSMITTED FORCES AND MOMENTS.

force measuring system. Here the support itself can be a streamlined strut of ample proportions to take the hydraulic loads without having to resort to the duplex construction used for the force measurements. Needless to say, models for these tests call for particular care in locating and forming the piezometer holes [11].

The water tunnel basically is suitable for investigation of the

effects of the exhaust on the hydrodynamic behavior of various jet propelled or ordinary internal combustion propelled devices. For this application means must be provided for supplying liquid or gas to the model. This can be done through hollow supporting strut members. Fig. 14 shows a model with an "exhaust" of compressed air supplied in this manner. When the fluid is a gas its removal from the circuit is difficult because the "negative settling time" necessary for bubbles to rise is usually longer than the time for complete recirculation of the water back to the working section.

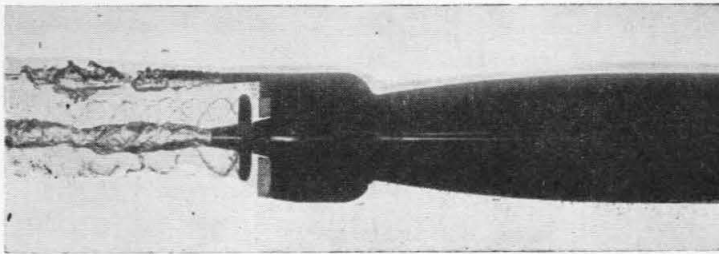


FIG. 14—MODEL FOR TESTING EFFECTS OF EXHAUST ON BODY WITH POWERED PROPELLER.

The example shown in Fig. 14 employs a powered propeller. The use of powered models is a necessity if the true flow conditions as experienced by self-propelled bodies in actual flight are to be duplicated. If the ratio of propeller tip velocity to forward velocity is to be the same in model and prototype, high propeller rotative speeds are required. For variable speed control the high-frequency synchronous motor is most satisfactory, but requires a source of "high cycle" current as an auxiliary to the water tunnel. Powered models have been widely used for wind-tunnel tests and some types of motors well suited for water-tunnel work are available. The electrical leads to the model also can be taken through the supporting strut. Simultaneous provisions for force measurements again complicate the construction.

Steady state forces as measured on stationary bodies in the water tunnel are not sufficient to determine the complete behavior of a free body in motion. In addition to the "steady state" forces and moments that are proportional to the yaw angle, it is necessary to know the "damping" forces and moments that are proportional

to angular velocity. The most satisfactory method of obtaining this information is to study a model having similar geometry and similar moments of inertia in actual free motion. However, techniques developed in the wind tunnel can be used in the water tunnel to obtain approximations which are satisfactory for many purposes. One method is to oscillate such a dynamically and geometrically similar body on a supporting spindle and to measure in effect the force and moment components resulting from angular velocity. This requires a special "dynamic" balance. The results are approximate because of support and wall interference effects. Another method arises from the fact that the damping cross force and damping moment are present when a free body executes a steady turn. This condition, which is one of a straight body in a curved flow, can be approximated in a tunnel by using curved models in the rectilinear flow. No auxiliary apparatus is needed besides the balance for measuring steady forces.

Remarks on instrumentation are not complete without mention of the importance of photographic observations. For some cases there are no more suitable methods of obtaining information about short-duration phenomena. The cavitation photographs included here are examples. Suffice it to say that a variety of camera and lighting equipment, including apparatus for "flash" and stroboscopic techniques, will find important application [12].

FUTURE TRENDS FOR WATER-TUNNEL RESEARCH

Promising Research Problems

Because of the particular advantages of the water tunnel it is logical that future research will emphasize investigations in which cavitation is a factor. A basic study of the cavitation phenomena itself is of fundamental importance. The mechanisms of bubble or cavity inception, growth, and collapse are almost completely unknown. Only meager information exists as to the effects on the production of cavitation of body shape, of velocity, of body size, of gases dissolved in the liquid, and of microscopic gas bubbles or foreign matter which might act as nuclei. The local pressures accompanying bubble collapse and the thermal and acoustic energy dissipation should be investigated. More information is needed about the effects of body shape for all stages of cavitation from the

incipient to the more advanced, but particularly for the extreme conditions such as shown in Figs. 7, 8, and 9. Both qualitative and quantitative approaches are necessary. The extremely short duration of the entire phenomenon of formation and disappearance of

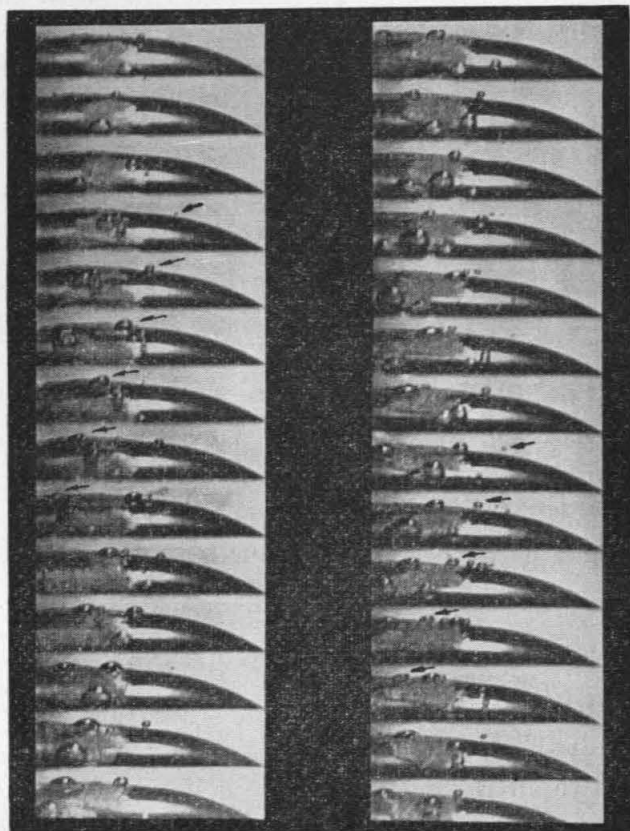


FIG. 15—GROWTH OF CAVITATION BUBBLES ALONG UPPER SURFACE OF OGIVAL BODY. INTERVAL BETWEEN PICTURES IS $1/3000$ OF A SECOND. (FLOW RIGHT TO LEFT.)

a single cavity makes a detailed study difficult. The use of ultra-high-speed motion pictures seems promising. Fig. 15 is an example of this technique, showing pictures of the growth of individual bubbles taken by a stroboscopic camera at 3000 frames per second.

Even this speed is insufficient to show all the details. It appears now that 50,000 to 100,000 frames per second will be necessary.

One of the applications of the results of cavitation studies is the cavitation analogue of the behavior of high speed airfoils. The determination of shapes suitable for supersonic speeds can be made

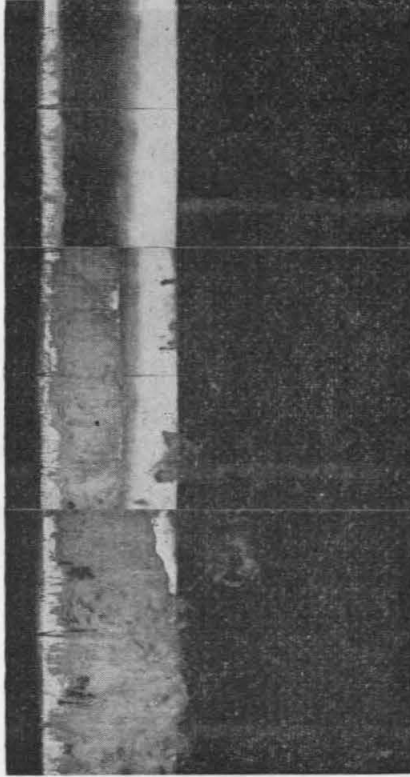


FIG. 16—LOW PRESSURE ZONES OUTLINED BY CAVITATION ON THE NACA 4412 AIRFOIL. FLOW VELOCITY = 45 FPS. STATIC PRESSURE IN FLOW = 49, 37, AND 23 PSI ABS. FOR UPPER, CENTER, AND LOWER PHOTOGRAPHS RESPECTIVELY. (FLOW LEFT TO RIGHT.)

by examining their cavitation characteristics. This, of course, can be done empirically, but with more information about the phenomena, rational design methods can be set up. Fig. 16 shows cavitation on the NACA 4412 airfoil shape. The zones of highest velocities, where compressibility effects will be experienced first, are clearly shown by the boundaries of the cavitating areas.

An extension of this is the design of high-speed bodies by using the shapes of the constant-pressure envelopes of the cavitation cavities obtained for advanced conditions. Fig. 17 shows the shape of a cavity obtained behind a circular cylinder. This analogy is applicable to three-dimensional as well as two-dimensional body shapes.

One of the serious problems currently under discussion is cavitation on hydraulic structures. A program of investigations of cavitation on shapes suitable for various structural components should be extremely fruitful. Fig. 18 shows an example of flow with cavitation around a streamlined strut.

The extension of this problem is to the study of shapes under partially submerged conditions. This is not a new aspect as the usefulness of model studies made with controlled atmospheric pressure is well established [13]. However, there is a need for a systematic and general study of body shapes under a wide range of velocity and pressure conditions. The high-velocity water tunnel with a working section modified for free surface operation, and with provision for a controlled atmosphere, provides a promising

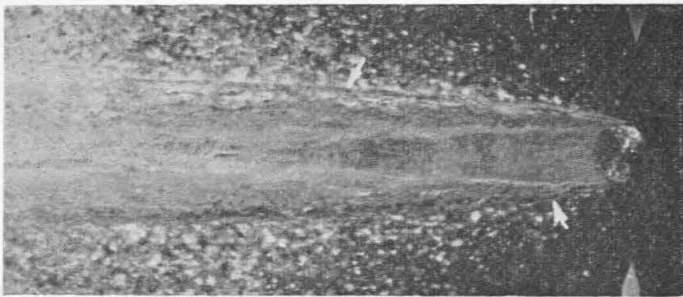


FIG. 17—CAVITATION CAVITY BEHIND CIRCULAR CYLINDER OUTLINES A SURFACE OF CONSTANT PRESSURE.

means of studying cavitation on shapes for baffle piers, piles and ship appendages, and even high-speed watercraft.

Of the many problems where cavitation is not solely important the effects of body shape on the hydrodynamic forces and moments should be the subject of additional systematic studies. The effects of shape on surface pressures is part of such a program. Important in this respect would be measurements of the range of fluctuating

pressures on and near bodies with flow separation or with cavitation. This will require development of instruments for recording instantaneous pressures. With the development of suitable instrumentation, boundary-layer and turbulence investigations, particularly as they influence cavitation, will prove important.

While application of the water tunnel to date has been entirely to studies involving a steady mean flow, investigations under vari-



FIG. 18—CAVITATION ON A STREAMLINED STRUT SUITABLE FOR USE AS PIER OR OTHER STRUCTURAL MEMBER.

ous conditions of accelerating and decelerating flow for stationary models, as well as models in motion, should prove useful. The extent of such applications will depend upon the development of methods of measuring continuously changing velocities, pressures, and forces. It is anticipated that electrical strain gage and pressure cell devices will be applied in this connection.

The Need for Basic Investigations

In conclusion, the desirability of directing water-tunnel research toward basic investigations should be stressed. In application of the water tunnel thus far, this has not always been the case. With both propeller and underwater ballistics research, the tendency has been towards studies for specific developments. While during the war years this course was completely justified, the water tunnel can be of greatest use in the long run if it is applied to the investigation of basic hydrodynamic problems. General principles thus compiled will help broaden the scope of rational hydraulics.

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