A Two-Dimensional Working Section for the High-Speed Water Tunnel at the California Institute of Technology

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Abstract

A brief historical account is given of the development of a well-known water tunnel, culminating in a new two-dimensional working section leg.

Limitations in the existing facility prompted a scale model study which verified the feasibility of critical features of the new design. Hydrodynamic design features include a novel transition nozzle, and a rectangular working section with walls which can be adjusted to control the longitudinal pressure gradient.

Mechanical design features are discussed which are aimed at solving model fabricating and support problems.

A brief description of the tunnel operating characteristics includes preliminary measurements and photographs of a base-cavitating wedge hydrofoil in the new working section.

Historical Background

The installation of the new two-dimensional working section leg (Fig. 1) to the High-Speed Water Tunnel at the Hydrodynamics Laboratory of the California Institute of Technology marks the most recent improvement in a long series, dating back to August 1941, when the late Robert T. Knapp first proposed a facility to be used for measuring the hydrodynamic forces on projectiles. Stimulated by war-time requirements, the tunnel was placed in operation early in the spring of 1942 [1].

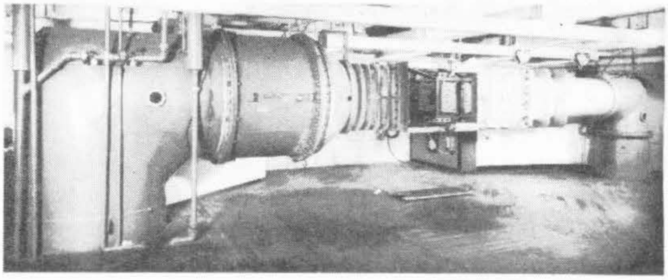


FIG. 1 THE NEW TWO-DIMENSIONAL WORKING SECTION LEG OF THE HIGH-SPEED WATER TUNNEL AT THE CIT HYDRODYNAMICS LAB. THE THREE COMPONENT FORCE BALANCE CAN BE SEEN SUPPORTED ON THE WORKING SECTION.

In order to meet the early completion deadline, many pieces of equipment were used which had been part of the Hydraulic Machinery Laboratory [2]. This equipment included the 250 kw motor-generator set, main drive motor-dynamometer, speed control system, constant frequency source, storage pump, pressure control system, cooling system, and a large vertical tank used as part of the circuit. Precision instruments, such as manometers and beam-type pressure gages, which had been developed for pump and turbine tests, were employed to measure the forces acting on the balance and the characteristics of the flow in the working section.

In this original configuration the tunnel was capable of a velocity of 70 fps with a controllable working section pressure ranging from four atmospheres to the vapor pressure of water. The models were supported in the 14 in. diameter circular working section.

Although this tunnel performed valuable pioneering work in the study of cavitation on underwater bodies, it did suffer some serious limitations. One problem was that air coming out of solution in the low pressure areas did not have sufficient time to redissolve before making subsequent passes through the working section. As a result the model became obscured by the increasing cloud of recirculating air bubbles.

After completion of the new laboratory building in 1945, the High-Speed Water Tunnel was moved into new quarters. In this move, those tunnel components, which had been part of the Hydraulic Machinery Laboratory, were returned to their former service and a new nozzle, diffuser, etc., were incorporated in the tunnel. A significant improvement in the operation of the tunnel was achieved through the use of the air resorber, a tank buried in the ground, which subjects the air-laden water to large hydrostatic pressure, thereby causing the air bubbles to be redissolved.. A new 350 hp dc motor enabled the tunnel to achieve a new operating velocity in excess of 100 fps while still retaining the independent pressure control in the working section. The working section instrumentation, including the balance, was carried over intact from the old tunnel [3].

As cavitating hydrofoils came into greater use, it became evident that a two-dimensional working section would be needed to study the section characteristics of proposed hydrofoils and to verify theoretical models of two-dimensional free-boundary flows. The working section was converted to the two-dimensional shape by placing a pair of ski-shaped inserts into the 14 in. diameter circular working section, thereby providing a passage with a quasi-rectangular cross-section, 3 in. × 14 in. [4].

At the same time basic modifications were made to the NPL type force balance which removed the existing ambiguous interaction between drag force and pitching moment inherent to this kind of balance. This interaction had necessitated the use of supplementary, internal pitching moment balances which were not compatible with the use of the balance for hydrofoil research. This problem was eliminated by adding a flexure-supported, moment-grounding platform between the balance and the model support spindle [5].

A reflection plane insert wall was also fabricated for this working section for use in studying three-dimensional flow on cavitating hydrofoils [6].

Need for the New Working Section

As experience was gained in the hydrofoil research programs, using the two-dimensional insert working section, it became apparent that this stop-gap device possessed serious operational and structural shortcomings. One of these was the lack of dimensional stability. Control of end-gap and spindle clearance was extremely difficult and tedious, resulting in some cases, in model configurations and clearances which were dictated more by practical considerations than by hydrodynamic requirements. More important, perhaps, were those shortcomings which tended to limit the range of operating parameters which could be chosen and measured during the course of a particular experiment. Low cavitation numbers could not be maintained for any length of time in this working section, because the vapor cavity at the end of the insert diffuser wall communicated to the dead water space between the insert and the tunnel wall, draining it free of water. When this happened the model was no longer visually observable. At the same time the loss in diffuser efficiency resulting from this cavitation, caused the tunnel velocity to decline steadily with time. Operating velocities which were already limited to 60 fps were thus further reduced, even though the small model size actually required higher velocities for Reynolds numbers to be in a useful range.

The problem of making an accurate measurement of the working section static pressure reference P_o was complicated by the fact that the walls were parallel only for a short distance upstream of the model location, and the most distant pressure tap location was 5½ in. ahead of the spindle centerline.

The longitudinal pressure gradient in the working section, due to the boundary layer growth and to the abrupt termination of the insert's diffuser wall, was accepted as being unavoidable and calibrations were performed to determine the value of the working section pressure as a function of longitudinal position.

Visual observations and photography were extremely difficult in this working section because of the small windows and because of the presence of air bubbles in the dead water region between the insert walls and the original tunnel windows.

The small model size dictated by limitations of the space available within the existing 14 in. diameter working section, made it difficult to perform systematic investigations of tunnel interference and blockage on cavitating hydrofoils. Space restrictions had also obviated the use of the tunnel for the study of hydrofoils in cascade, an area of experimentation which will be valuable for systematic research programs aimed at the development of super-cavitating blades for rotating machinery.

Tunnel Hydrodynamic Design Features and Model Study

Consideration of the foregoing limitations on the existing equipment dictated the following hydrodynamic requirements for the proposed new two-dimensional working section leg:

1) The working section should permit use of models approximately 6 in. in span and 6 in. in chord.

2) The height of the working section should be approximately five times the model span, or 30 in., to insure that these walls would not have too great an effect on the bubble geometry and would not produce too high a choked cavitation number for models of practical thickness.

3) The *straight* section of the working section should be long enough to permit the study of the long cavities which will exist at low cavitation numbers. On the basis of the experience with the existing two-dimensional working section, this was taken to be 50 in.

4) The working section should be equipped with adjustable side walls to permit control of the wall spacing and hence the longitudinal pressure gradient as a means of compensating for boundary layer growth and studying the effect of this gradient on bubble geometry and model force characteristics.

5) The working section must be capable of convenient rotation about the longitudinal axis so that the pressure gradient due to gravity can be in the direction of either the 6-in. dimension or the 30-in. dimension, depending upon the particular kind of model in the tunnel. For the study of hydrofoils in cascade, it would be essential to minimize the differences between the cavitation numbers of widely separated hydrofoils, but for a single model under investigation it would be more desirable to minimize the span-wise variation in cavitation number.

6) The new working section leg must be compatible with the existing tunnel, and readily interchangeable with the present 14-in. diameter circular working section leg. Existing balances, manometers, and attachments should, wherever possible, be able to be used on both legs.

These general specifications could best be met by replacing the existing nozzle, circular working section and two diffusers of the present tunnel with a new transition nozzle, two-dimensional working section, two-dimensional diffuser and a transition diffuser, respectively.

In addition to meeting these specific hydrodynamic requirements it was considered essential that the flow in the working section be as free from turbulence as possible, that the velocity profile should be flat over a large part of the cross-section area, and that the boundary layer at the walls be as thin as possible. A tunnel which is to be used for cavitation studies possesses the additional restriction that the minimum pressure exists at the working section itself, since any cavitation upstream of the model would disturb the direction of flow over the model, as well as obscure visual observation.

The new transition nozzle was required to contract the flow from the existing 60-in. diameter settling chamber, downstream of the honeycomb, to the 6 in. by 30 in. rectangular cross-section of the proposed working section. The nozzle for the existing 14-in. diameter circular working section performed this contraction in a distance of 60 in., so it was decided to limit the new transition nozzle to this same overall length.

Past experience with non-circular contracting nozzles indicated that serious flow problems could result from unequal boundary layer growth and boundary layer interaction at sharp corners. It is well known that the performance of a contracting nozzle of circular cross-section is relatively insensitive to the specific shape of the contraction and that a smoothly accelerated flow based on a one-dimensional calculation (using measured cross-section areas) will usually produce a satisfactory flow at the working section. Following this procedure a curve of areas was constructed for existing contracting nozzles in use at the laboratory, and the curve of areas for the proposed transition nozzle was drawn by interpolating values between these. All of these existing nozzles had been designed using modifications of the Tsien method [7].

Given the prescribed curve of areas, it is still impossible to design a nozzle of constantly varying shape, unless some method can be found which prescribes the cross-sectional shape corresponding to a given station. The method described below was chosen only because it offered a systematic, rational approach.

A catalog of shapes related to cross-section areas was compiled, where the shapes were determined by stretching a thin, rubber membrane between a circular disc and a rectangular plug of the correct size and shape protruding from it (Fig. 2). A plaster cast was made of this three-dimensional shape, which was subsequently planed in a milling machine to obtain cross-sectional shapes of successive horizontal layers. The area of each of the resulting sections was measured using a planimeter, and selected ones distributed longitudinally, in accordance with the prescribed curve of areas. The resulting form was "reasonable and fair." An interesting feature of this shape was that the first sections after the 60-in. diameter circular shape were very nearly elliptical, increasing in eccentricity as they approached the rectangular working section. Also, the final contraction was nearly two-dimensional, the 30-in. height not changing perceptibly

FIG. 2 RUBBER SHEET STRETCHED BETWEEN CIRCULAR SECTION AND RECTANGULAR SECTION AT DIFFERENT ELEVATIONS. HORIZONTAL SECTIONS OF THIS SHAPE WERE USED TO RELATE AREA TO CROSS-SECTION SHAPE FOR THE FINAL NOZZLE DESIGN.

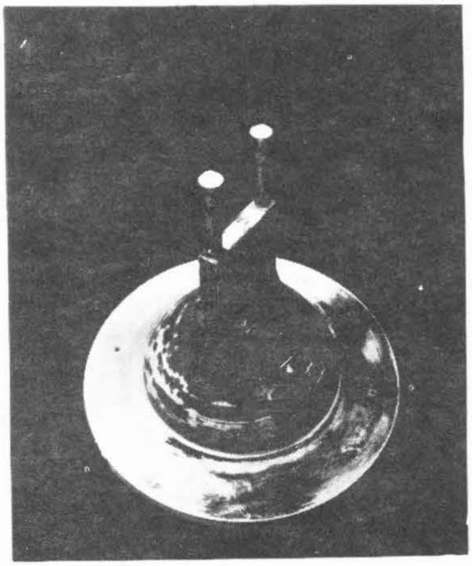


FIG. 3 NOZZLE CONTOUR AS DETERMINED BY SELECTED TEMPLATES SPACED ACCORDING TO THE PRESCRIBED CURVE OF AREAS. THIS PLUG SERVED AS THE FORM FOR THE 1/6-SCALE MODEL NOZZLE.

for the second half of the contraction. Metal templates were made corresponding to the selected stations, then spaced on a pair of metal rods mounted in a circular face plate. Casting plaster was then packed into the spaces between the templates and carefully faired with flexible splines, until a pleasing, smooth form was obtained (Fig. 3). Because of the difficulty which would have been involved in making the prototype directly, this procedure was used on a 1/6th scale model. Using this plaster form a fiber-glass epoxy nozzle was fabricated with a 1-in. by 5-in. rectangular opening at the discharge end. This model nozzle was installed on an existing 10-in. line in the Hydraulic Machinery Laboratory.

The model nozzle was operated as a free jet, at velocities up to 50 fps and both the nozzle wall pressure and discharge velocity profiles were measured. The pressure along the nozzle wall varied monotonically from entrance to exit in both the horizontal and vertical planes, while the discharge velocity profile deviated less than 1/4 per cent over that part of the exit area not within the boundary layer.

Measurements of boundary layer thickness were also made, but the large diameter of the available probes precluded accurate determination of this value.

After the model nozzle was completed and tested, a model working section was fabricated and fastened to the nozzle. Pressure measurements were repeated both along the nozzle and in this parallel-wall working section. The pressure distribution was smooth, varying monotonically from the circular inlet section to the rectangular discharge at the downstream end of the working section.

Smoke and tuft tests were also performed in air on the model nozzle. For these tests, the downstream end of the model working section was attached to a vacuum plenum. At the upstream end of the nozzle a bell-mouth, honeycomb and transparent settling chamber were relied upon to provide smooth entry conditions. Neither the tufts nor the smoke gave any indication of flow separation, or of circumferential flow in the nozzle or working section.

At the completion of the model study, a full size drawing of the prototype nozzle was made from the model and the mechanical design for the entire leg was undertaken.

Prototype Design Features

The Nozzle. The nozzle is a ribbed, two-piece, Meehanite casting, handfinished on the inside to present smooth, faired curves to the flow. The structure is designed to operate between a pressure 100 psig and a vacuum of 1 atmosphere. A large rim located near the big end of the nozzle acts as a guide for a roller chain which will be used to rotate the working section through 90 degrees as explained in the preceding section. O-ring seals are provided on the flanges which make up to the existing tunnel settling chamber and to the new two-dimensional working section.

The Working Section. The salient mechanical and hydrodynamic features of the working section itself are shown in the schematic diagram of Fig. 4. In this drawing can be seen the massive, box-like beams which form the

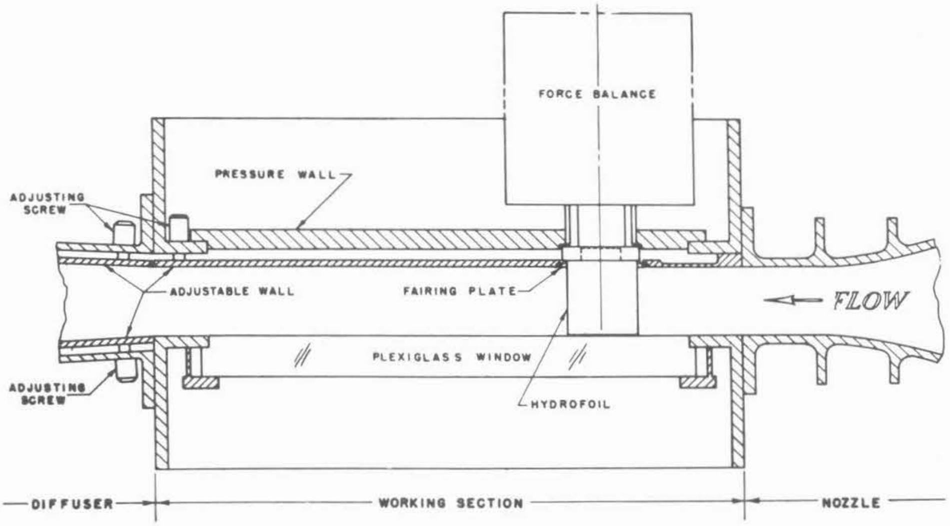


FIG. 4 SCHEMATIC DIAGRAM OF THE TWO-DIMENSIONAL LEG WORKING SECTION AS SEEN FROM ABOVE.

four corners of the working section and which serve to provide structural stiffness under the large range of pressures to which it is subjected. This degree of stiffness is essential if the working section dimensions are to remain fixed and if the model end gap is to remain reasonably constant, while still providing for unimpaired observation through the large lucite window. This window is parallel to the theoretical centerline of the tunnel. On the balance side, the bounding wall is flexible and rigidly attached to the tunnel only at the upstream, or nozzle end. Downstream its position is determined by a series of adjusting screws, which protrude through the tunnel pressure wall, and which are covered with water-tight seal caps. This wall can be adjusted to a position where it is approximately parallel to the theoretical tunnel centerline or to where it diverges, being wider at the downstream end than at the upstream end. In this latter configuration, it can be seen that the tunnel is not accurately symmetrical. This adjustment gives the operator some measure of control over the longitudinal pressure gradient which exists in the tunnel. It is possible to choose a configuration where the midstream velocity either increases or decreases in the downstream direction. Although the tunnel wall divergence will be maintained at a fixed value for most experiments, it may not always be possible to establish beforehand what this value will be, therefore making it difficult to determine the required span of a given hydrofoil. This problem is solved by mounting the balance normal to, and at a fixed distance from, the far side plexiglass window, regardless of the position of the adjustable tunnel wall on the balance side. The model passes through an aperture in the adjustable wall. In this way the model can be finished with a square tip, perpendicular to the span, and it can be rotated through any angle of attack without this far side gap undergoing variation. This feature results in minor problems at the balance end. which are described below.

It is anticipated that the large lucite window will be replaced by special metal ones for investigations involving hydrofoil cascades, dummy model supports, wake traverses, etc. These windows are readily interchangeable, using an overhead hoist which suspends the window over its center of gravity. Full length windows along the smaller sides of the working section were designed to provide an unobstructed view of the edges of the adjustable wall and of the edge of the large transparent window; past experience having indicated that visual inspection of model gap clearance, survey probe location, and cavity bubble shape near these walls to be always of primary interest.

Model Mounting Provisions. The cost and accuracy of a hydrofoil model are both usually compromised unless a hydrofoil can be fabricated in unlimited lengths, i.e., by maintaining a constant cross-section shape and by avoiding abrupt enlargements at the end of the span for mounting purposes. This simple procedure is difficult to follow, however, since the strength and rigidity requirements of the hydrofoil usually demand that it be solidly attached to the model spindle. Also, because of the desire to avoid gaps of any kind near the high pressure regions of the hydrofoil, it has become general practice to mount the hydrofoil from a relatively large diameter disc flush with the wall. An arrangement which provides both of these features has been adopted for use in the new two-dimensional leg. A view of a 7½ degree wedge hydrofoil is shown dismantled in Fig. 5 and in place in the tunnel

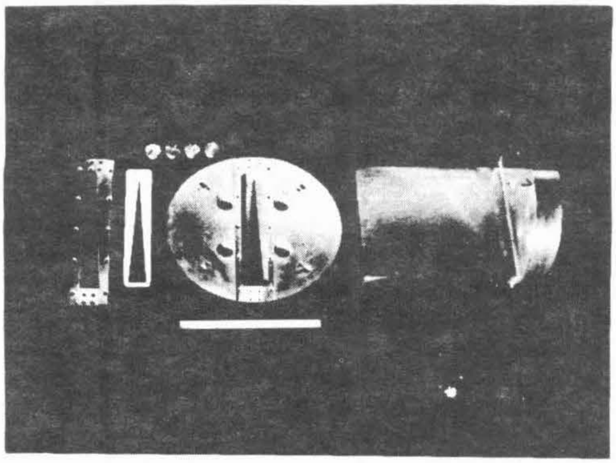


FIG. 5 7½ DEGREE WEDGE HYDROFOIL MODEL ASSEMBLY DISMANTLED, SHOWING MODEL POTTED INTO SUPPORT DISC, FAIRING PLATE, AND RUBBER SEAL.

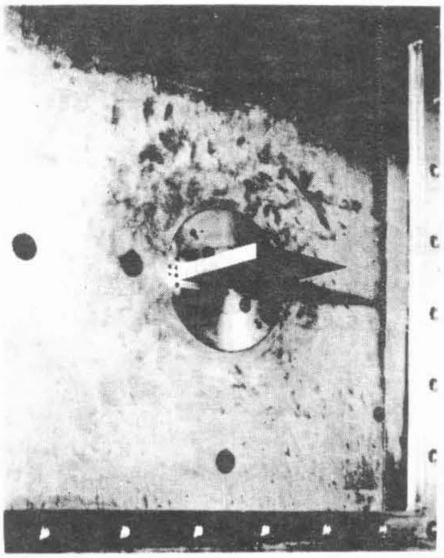


FIG. 6 7½ DEGREE WEDGE HYDROFOIL MODEL MOUNTED IN PLACE IN THE TWO-DIMENSIONAL WORKING SECTION. THE FAIRING PLATE HAS BEEN ADJUSTED TO PROVIDE A CONTINOUS SURFACE WITH THE FLEXIBLE WALL THROUGH WHICH THE MODEL PROJECTS.

working section in Fig. 6. The stainless steel model, which in this case was ground, then lapped, to final dimensions is potted into its aluminum support disc. A pair of stripper bolts, accurately located in the model prior to machining, position the model and provides temporary fastening until the model has been potted. The potting material used is a commercially available low temperature melting point alloy. A large fairing plate slips over the model and is supported a short distance away from the mounting disc, by means of adjustable push-pull screws. The aperture in the fairing plate is, in turn, sealed with rubber cast in place using a room-temperature vulcanizing elastomer. Because the tunnel walls may diverge slightly, it is necessary to provide for adjustments in the angle of the fairing plate. If a wide range of angles of attack is employed, it may be necessary to readjust the fairing plate during a run to eliminate the ledge which appears because of the nutation of the plate.

To facilitate model alignment and to insure interchangeability, drill jigs were fabricated for each of the parts, thus insuring that all models be identically located and that model end gaps and disc clearance gaps be as small as possible.

Tunnel Operating Characteristics

The new leg of the tunnel has been in operation for less than two months and although the pressure to complete present programs has not permitted detailed surveys to be made, preliminary results indicate that the hydrodynamic and mechanical design goals have been met. Furthermore the expectations from the model program were generally borne out. Since the first experimental programs have not called for tunnel velocities in excess of 50 fps, it was decided to perform all calibrations and surveys at velocities below this value, although extrapolation of tunnel power requirements indicate that it will achieve the design maximum speed of 85 fps. The tunnel velocity, as measured by taking the pressure drop across the nozzle, remains very steady at all speeds over a wide range of working section pressures with no indication of premature cavitation either in the nozzle or in the diffuser. When cavitation does occur it is along the upper window of the working section where the hydrostatic pressure is lowest. If the tunnel working section were rotated so that the 30-in. dimension would be horizontal, then still lower values of centerline working section pressure could be obtained before the onset of tunnel cavitation.

Another method of avoiding cavitation of the tunnel while still obtaining low effective cavitation numbers on supercavitating hydrofoils is through the use of controlled air ventilation. Small amounts of air introduced into the low pressure region on the model, increase the cavity pressure without any primary effect on the pressure distribution along the tunnel itself. The cavity pressure must then be measured, of course, instead of merely assuming it to be equal to the vapor pressure at that temperature, but this task presents no real difficulty.

Although the tunnel has no present provision for removing the air introduced in this way, no trouble has ever been experienced with recirculating bubbles; the air either dissolves completely or it accumulates in the top of the resorber tank. For large air injection rates, the duration over which tunnel pressure can be maintained at a low value is limited by the apparent volume change, but a simple air bleeding procedure returns the tunnel to immediate use.

Measurement of Tunnel Working Section Pressure. The problem of determining the value of the reference static pressure P_o in a water tunnel is a difficult one at best, and it increases both in difficulty and in importance when experiments are performed using two-dimensional supercavitating hydrofoils. The specification of the cavitation number $(P_o - P_k)/(\frac{1}{2}\rho\, V_o^2)$ is extremely important for insuring dynamic similitude, yet the numerical value of $P_o - P_k$ is so small in the interesting range of cavitation numbers that the effect of the pressure field of the model on the tap which measures P_o is an important source of error. To help solve this problem, pressure taps have been located at many selected points along the nozzle wall as well as along the wall of the working section. The pressures at these points are being determined for various operating velocities with the bare tunnel, so a comparison can be made when a model is placed in the tunnel and subjected to lift and drag forces. When completed, these calibrations will permit an accurate determination both of tunnel velocity and cavitation number for any model installation.

Another technique being considered makes use of a special pressure tap located far enough upstream in the nozzle to be practically out of the pressure field of the model. This tap will be mounted at the end of a plug inserted through the nozzle wall and so shaped as to create a small bump in the nozzle wall. The size and shape of this bump will be adjusted until the local pressure drop will be exactly equal to that due to the remaining length of nozzle, so that the pressure measured at this point will be identical to the working section pressure over some range of useful velocities.

Horizontal Pressure Gradient. The effect of boundary layer growth in a parallel-sided tunnel working section is to cause a slight increase in the velocity of the main stream along the tunnel centerline. For fully wetted flow the effects of this acceleration and of the accompanying pressure drop is to introduce spurious horizontal forces. For supercavitating flows the effects have not been completely investigated, but they can be expected to have pronounced effect on cavity shapes.

When the new leg was first assembled, the working section walls were made parallel and the resulting pressure gradient determined for several velocities. Subsequent adjustments and more detailed pressure measurements resulted in negligible pressure gradient for the bare tunnel (see Fig. 7). This configuration was the only one used in recent hydrofoil experiments, but future plans call for investigation of the effect of controlled longitudinal pressure gradient in supercavitating flows.

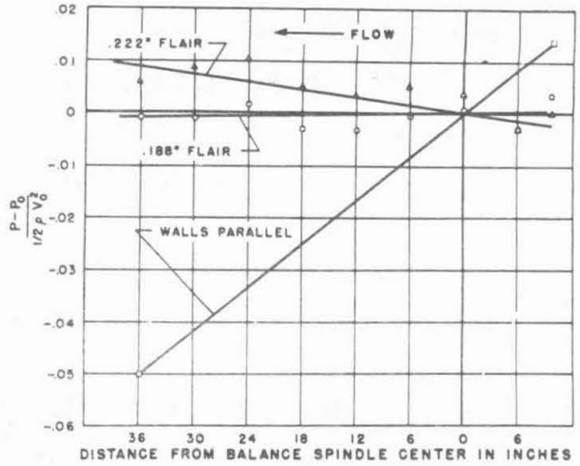


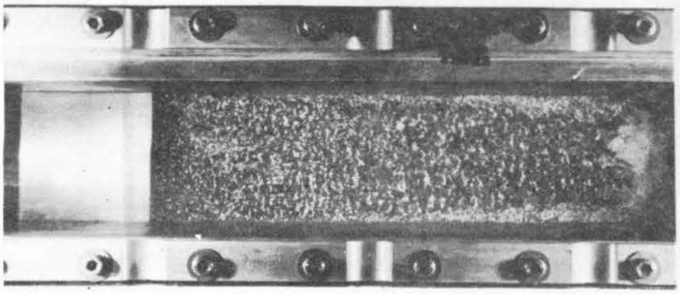
FIG. 7 LONGITUDINAL PRESSURE GRADIENT ALONG THE WORKING SECTION CENTERLINE FOR A BARE TUNNEL WITH VARYING AMOUNTS OF LATERAL WALL DIVERGENCE.

Experimental Programs

The first program performed in the new two-dimensional leg was a study of the influence of gravity on the flow past base-cavitating wedges. Fig. 8 shows a 7½-degree wedge hydrofoil, as seen from below, at the same cavitation number, but at two different velocities. The appearance of the re-entrant jet for this same bubble length shows the striking effect of Froude Number difference. Since data reduction for the calibration runs have not yet been completed, the cavitation numbers and velocities are uncorrected for possible influence by the model pressure field. A small amount of air was injected into the cavity to insure freedom from possible disturbances by tunnel window cavitation.

Future programs for the tunnel will be directed in many different areas. One of these is the investigation of scale, blockage and wall interference effects in cavitating flows. Another is the study of nonsteady forces in cavitating and non-cavitating flows. These latter investigations will make use of a new electro-hydraulic oscillator and dynamic balance which has recently been completed. This oscillator is capable of producing oscillations with a pre-determined program of displacement, velocity, in the heaving mode, at frequencies up to 100 cycles per second.

The generous dimensions of the working section will be used also for the study of hydrofoils in cascade. The central hydrofoil will be attached to the tunnel balance



Velocity = 20 fps $C_D = .178$ $K = .12$

Velocity = 40 fps $C_D = .176$ $K = .12$

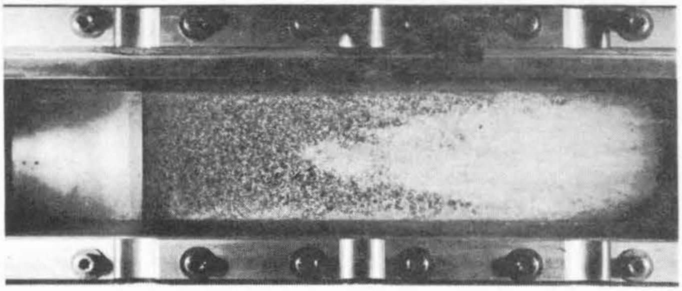


FIG. 8 7½ DEGREE WEDGE HYDROFOIL, SEEN FROM BELOW, SHOWING THE EFFECT OF VELOCITY ON THE APPEARANCE OF THE CAVITY AND RE-ENTRANT JET. DRAG COEFFICIENTS ARE BASED ON CROSS-SECTIONAL AREA.

while the other hydrofoils in the lattice are rigidly attached to the tunnel wall. Turning of the flow will be achieved through the use of special ramps inserted along the narrow walls of the working section.

Acknowledgment

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