CAVITATION

AND

PRESSURE DISTRIBUTION

Head Forms at Angles of Yaw

By

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I. INTRODUCTION

In 1948 Dr. John S. McNown and the writer published as Bulletin 32 of this series a compilation of pressure measurements that had been made during the war years on several families of axisymmetric head forms at zero angle of yaw for cavitating as well as noncavitating conditions. In the Introduction it was confidently stated that the investigation would ultimately include both two- and three-dimensional head and tail forms at various angles of yaw. Despite the changes of emphasis and interest that came with the postwar period, continual efforts were made to carry out at least the yaw portion of the program. Later in the same year, in fact, an M.S. thesis was submitted by C. A. Lamb under the title "The Effect of Angles of Yaw on Pressure Distribution around Various Head Forms," but for almost a decade this represented the only tangible experimental progress that was made.

Although the 1943 water tunnel that had been used for the initial experiments was replaced in 1951 by one that had been designed to eliminate many of the faults of the original unit, successful operation of the new one (at least for the yaw studies) seemed to require still greater skill. Such skill is not acquired in a day or even a month, yet the Institute must rely upon its graduate-student staff members for most of its experimental accomplishment. One after another contributed time and effort to the study, but never for a sufficiently long period to provide data that would form an essential part of the proposed systematic investigation. Not till nearly ten years had passed did a favorable succession of advanced students begin to produce results; one designed an effective mount for the heads over an extreme range of yaw angle; one devoted an extra year of time to the measurements; two thereafter systematized his results; and one, finally, completed
Fig. 1. Longitudinal Section Through Water Tunnel.
Fig. 2. Auxiliary System for Controlling Pressure.

Fig. 3. Details of Test Section and Shaft Support.
the detailed plots contained in this bulletin. Except for the year in which the measurements themselves were made, when he was on leave of absence, the writer had general charge of the project.

Aside from overall dimensions, internal finish, and type of drive, the new water tunnel was essentially the same as the old in range of velocity and pressure and method of operation. The eight interchangeable heads studied at angles of yaw were chosen from the twenty-odd of 1-inch diameter that had formed the basis of the earlier investigation. Deterioration in the 1-inch supporting shaft previously used, together with the necessity of mounting it in such a manner as to provide optimum variation in yaw angle, made it necessary to rebuild it, but the same piezometer locations were retained. Since full details of tunnel operation, head and shaft geometry, and related factors are given in Bulletin 32, it is assumed that the two bulletins will be used together, and only material that is essentially new will appear herein.

II. Experimental Equipment

The water tunnel shown in the Frontispiece and Fig. 1 was built with Institute funds to match in every detail but the test section a second one that had been built in 1949 with funds provided by the Office of Naval Research. Whereas the ONR tunnel had a closed-throat test section with a 24x6-inch rectangular flow passage for two-dimensional studies, the Institute tunnel was provided as before with an axisymmetric open-throat nozzle of the same cross-sectional area—i.e., 1 square foot, the diameter of which is about 13.5 inches. All wetted parts of the tunnel proper were fabricated of stainless-clad mild steel to eliminate the necessity of painting the inner surfaces. The pump is a 30-inch axial-flow unit manufactured by the Peerless Pump Division of the Food Machinery and Chemical Corporation. It is driven by a 3000-RPM 65-HP AC motor through a 7:1 gearbox and a positive-displacement type of hydraulic control permitting continuous variation in speed from zero to a maximum of 500 RPM, the latter yielding a velocity of about 40 feet per second at the test section. A comparison of Fig. 1 with the corresponding figure of Bulletin 32 will indicate that the new tunnel, although possessing essentially the same test-section dimensions, is otherwise much more efficiently designed and powered. Pressure controls, the circuits of which are indicated in Fig. 2, are practically unchanged in general form.

In order to support shaft and heads with maximum rigidity and minimum flow disturbance, and yet permit variation in yaw angle from 0 to 90°, a streamlined stainless-steel arc and vise-like guides were fabricated as shown in Fig. 3. The shaft was smoothly mounted near the midpoint of the
arc (with freedom to rotate 45° about its axis), the head of the drawbar holding the head forms in place being faired into the arc. The lower part of the arc was left hollow to accommodate the 24 piezometer leads, and two sections could be transferred from one end to the other, so that the arc would be supported by at least three of the four guides at all angles of yaw. Only one of the guides extended slightly into the flow, but a well-faired stationary tailpiece spanning the receiver ring provided additional stability to both flow and shaft. Proportioning the receiver ring to yield reasonably pulsation-free flow with a negligible pressure gradient in the vicinity of the heads required a considerable amount of time (a small air tunnel of approximately the same proportions being used to good advantage in the preliminary study). The pressure distribution on the axis of the test section as read from piezometers along the shaft and a special head that extended well into the nozzle is seen in Fig. 4; the reference value \( h_n \) is that read on a piezometer \( \frac{1}{2} \) inch from the nozzle lip. The computed curve shown as a broken line was based upon the irrotational flow ahead of a linear strut having the same cross section as the arc. Because of the unknown pressure effect of the ring, the computed curve was arbitrarily passed through the other at the pivot point. The velocity distribution again varied less than 1% from the mean throughout the zone of interest.

Although, since no new heads were to be made, the choice of profiles to be tested was limited to some degree by imperfections that had developed in several of the specimens, the eight finally selected were quite representative of the four series that had previously been studied. Of the rounded series, these included the 2-caliber ogival, the hemispherical, and the blunt; of the conical series, the 45° conical and hollow cylindrical (and again force the blunt); of the semiellipsoidal series, the 4:1 and 2:1 (and perforce the hemispherical and blunt); and of the supplementary series, the \( d/2:d/4 \)
modified ellipsoidal. The overall characteristics of these forms are indicated in Fig. 5; for further detail, reference should be made to Bulletin 32 and the summary plots at the end of this bulletin.

![Diagram of different head forms](image)

**Fig. 5. Head Forms Selected for Yaw Investigation.**

### III. Test Procedure

Preliminary runs at a lower pressure than that of the test run proper were invariably made for purposes of deaeration, just as in the series described in the previous bulletin, whereafter all parts of the tunnel, including the piezometric leads, were carefully bled. For a particular angular setting of the shaft and head (the null position having been determined as that at which the same pressure distribution prevailed along the top and bottom), a pump speed yielding a test-section velocity of about 15 feet per second was established, and readings were obtained for each of the piezometers along the top and bottom of shaft and head with a sufficient pressure load on the tunnel to ensure a cavitation index well above the incipient. Since most of the heads contained piezometric openings at various angular locations around the circumference, the head or shaft was then rotated about its axis to bring the other openings to top or bottom and additional measurements were made. (Though measurements were possible at any other point around the circumference of head and shaft, only those at top and bottom were undertaken systematically.)

The foregoing procedure was repeated under flow conditions so chosen as to yield such of the regular sequence of cavitation indices 0.8, 0.6, 0.4,
and 0.2 as lay below the specially determined point of incipience for the 
given head and yaw angle. In the previous investigation, the velocity had 
been held constant and the pressure load decreased till the desired magni-
tude of the index was attained, so that the Reynolds number remained 
essentially constant through the study. In the present investigation, on the 
contrary, the pressure load was held constant and the velocity was in-
creased till the index reached the desired magnitude, as a result of which 
the Reynolds number was the higher, the lower the cavitation index. Un-
fortunately, the writer did not learn of this departure from normal practice 
until it was far too late to repeat the runs. Fortunately, on the other hand, 
the experimental discrepancies appeared to be small—at least so far as 
could be seen from a comparison of data for the old and new runs at zero 
angle of yaw.

Measurements of this nature were made systematically for each of the 
head forms at selected angles of yaw ranging from 0° to 90°. The hemi-
spherical, blunt, and hollow heads were considered of broader significanc
than the others, and for these the selected angles were $0^\circ$, $6^\circ$, $15^\circ$, $30^\circ$, $45^\circ$, $60^\circ$, and $90^\circ$. For the remaining heads, the $30^\circ$ and $60^\circ$ positions were omitted.

The velocity and pressure measurements were made as before by means of a mercury differential manometer reading to 0.001 foot. The vapor pressure of water was evaluated from standard tables according to the measured water temperature, the partial pressure of air released from solution being ignored. Piezometric readings along the shaft were corrected according to the axial distribution shown in Fig. 4, under the simplifying assumption that the pressure field varied longitudinally but not radially.

A photographic record was made of the mean cavitation pattern for each head form, yaw angle, and cavitation index investigated, using rear lighting and an exposure of $1/25$ second. Although only a few were of sufficient quality for halftone reproduction (see Fig. 6), the pocket silhouettes are on file for reference purposes and provide a significant basis for comparing the various states of motion.

IV. Discussion of Results

All experimental data are presented in comprehensive form in the eight fold-in plates at the end of the bulletin. For convenience of comparison, each plate contains the diagrams for the successive angles of yaw of a single head form, the individual diagrams comprising as before the curves for different values of the cavitation index. Now, however, each curve except those for zero yaw extends over negative as well as positive values of the developed profile length $s/d$; negative values correspond to the lower or upstream side of the profile, and vice versa. The order of the diagrams is the same as that indicated in Fig. 5.

The plots inserted at the upper left opposite the zero-yaw diagram in each series were prepared long after the experimental measurements had been made, so that there was no longer a possibility of repeating runs in which inconsistencies appeared. Since less emphasis than before had been placed upon a careful evaluation of both the minimum nondimensional pressure and the index of incipient cavitation, and since the effect of separation and eddy cavitation tends to become more pronounced with increasing yaw, considerable scatter of data is found in most of the plots. Nevertheless, the mean curves show rather consistent trends of at least qualitative significance.

Once again the hemispherical head (Plate I) is probably the form of greatest interest, for not only is it the one most frequently encountered because of its relative ease of fabrication, but it possesses a sufficient degree
of curvature for analytical predictions to be more than qualitative, and at the same time a sufficient degree of bluntness for at least slight separation to occur. The familiar sequence of curves for zero yaw is seen to be only slightly modified at 6°. At 15°, however, the effect of additional separation is evident behind the head, and at 30° this is the more pronounced. Separation has become so great at 45° that there is a considerable numerical difference (refer to upper left-hand plot) between the minimum nondimensional pressure and the index for incipient cavitation. That the separation zone is decidedly three-dimensional at 45° is seen by the pressure peak a short distance behind the head. Further evidence of the secondary motion that is produced in the wake is found by visual (and photographic) observation of the cavitation pocket. These effects continue through the 60° position but are somewhat alleviated as 90° is approached. At this limit the front of the shaft is seen to become a zone of stagnation, except in the immediate vicinity of the head itself, for all conditions of cavitation. In Fig. 7 is shown the variation in pressure with yaw angle at the stagnation-pressure and ambient-pressure points of the unyawed profile. The significance of these curves in flow measurement is discussed in the writer's paper on the subject in the Riabouchinsky anniversary volume, Ministère de l'Air, 1954.

The blunt head (Plate II) is nearly as far in the direction of nonstreamlining as one can go, as a result of which cavitation begins in the eddies generated along the surface of separation, and the index for incipient cavitation is much greater numerically than the minimum nondimensional pressure. As the angle of yaw is gradually increased, the separation zone becomes larger and less intense on the top or downstream side and smaller but more intense on the bottom or upstream side, where the zone of minimum pressure—at least for the higher cavitation indices—now lies. With increasing angle the pressure distribution on the blunt face also becomes more and more asymmetric. At 30° the stagnation point has nearly reached the leading edge. At 45° it is already beyond the edge on the front side, and the rear half of the face is under negative pressure though still free from separation. At 60° separation has begun at the leading edge, and flow in the rear of the shaft has taken on some of the three-dimensional aspects already noted for the hemispherical head. Except for conditions at the very tip, the distribution curves for the 90° limit are not greatly different in the two instances.

Extreme lack of streamlining is found in the hollow cylindrical head (Plate III), as a result of which a considerable departure in performance from even the blunt head is to be seen on all diagrams but the first. Only at small angles of yaw (6° and 15°) is the zone of lowest pressure at the front edge. There is also a pronounced modification in end effect at the intermediate angles, for a form such as the hemispherical tends to facilitate

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end flow whereas one like the hollow tends to resist it. The three-di­
men­sional effect in the wake is shifted accordingly to a lower angle range. The
greatest distinction, of course, occurs in connection with the pressure
within the head. Long after the completion of the tests, a piezometer (No.
0) was added on the centerline, and such runs as were necessary to deter­
mine the pressure under noncavitating conditions were made at the differ­
ent angles of yaw. These are indicated at the midpoint of the abscissa
scale. (In this connection it should be noted that, except for its position of
symmetry, the plotted point bears no relation to the abscissa scale, since

![Figure 7: Measured and Computed Variations in Piezometric Head at Tip and Neutral Points.](http://ir.uiowa.edu/uisie/42)

for want of any better origin the developed distance was assumed to begin
at the leading edge of the head.) Although data for various intensities of
cavitation are now at hand, the fact that separation takes place at all angles
even without cavitation would lead one to expect little change to occur
with increasing cavitation intensity. On the other hand, the supplementary
pressure readings did reveal what appeared to be a Reynolds-number ef­
fect at large angles of yaw, as indicated by the double centerline points at
60° and 90°. One must suspect therefrom that all curves at these angles
may be subject to a comparable displacement. For noncavitating condi­
tions, the variation in internal pressure with smaller angles of yaw is of
special significance in connection with Pitot-tube indication. The stagnation
limit is seen from Fig. 7 to prevail over an angular range of ±25°. This corresponds, of course, to a tube with very thin walls; the other limit is represented by the center opening of the blunt head, the pressure function of which is also shown in Fig. 7.

The 45° conical head (Plate IV) is probably at the other extreme from the hemispherical in importance. Of academic interest is the tendency of the stagnation point to remain at the tip (albeit at one side of the tip at larger angles) until an angle of probably 90°−45°/2=67.5° is exceeded. A definite anomaly is found in the decrease (rather than the usual increase) in pressure over a considerable portion of the head at an angle of 45° as cavitation begins.

Of the several semiellipsoidal heads, the 4:1 (Plate V) is by far the best streamlined—and hence the least susceptible to cavitation—at zero yaw but not at all other angles. In fact, whereas increasing the axis ratio of such a profile eases the curvature in the low-pressure zone at zero yaw, it tends to do just the opposite at moderate to large angles. The 1:1 or hemispherical head thus displays a much smaller variation in minimum pressure with yaw angle. On the other hand, separation effects seem to produce an increased tendency toward cavitation behind the hemisphere at large angles. As was shown by Lamb in the thesis previously mentioned, at the small angles investigated (3° and 6°), the analytical solution for the pressure distribution in irrotational flow around a full ellipsoid yields fairly good results for the semiellipsoid at the end of a cylindrical shaft. The extent of the agreement at the various angles of yaw is shown in the diagrams by broken lines. (Better agreement, of course, would result from a closer analytical approximation to the composite boundary form.) The curves plotted in Fig. 7 for the pressure variations at the tip and the neutral points likewise differ little from the computed values. Herein the function for the neutral points is seen to be almost linear over a considerable range—a fact of potential value in pressure and velocity instrumentation.

The 2:1 semiellipsoidal head (Plate VI) is, as one would expect, intermediate between the 4:1 and 1:1 (i.e., hemispherical) in essentially every characteristic. Reference is hence made to the foregoing discussions and the several pertinent plots.

In devising the series of modified-ellipsoidal forms studied at zero yaw in the previous investigation, an effort was made to alleviate the tendency toward cavitation by easing the curvature in the zone of minimum pressure—without, however, reducing the pressure even further by exaggerating the curvature at another point of danger. The d/2:d/4 modified-ellipsoidal head (Plate VII) was neither the best nor the worst of those previously tested—about the equivalent of the 2:1 semiellipsoidal, in fact. At the intermediate angles it is evidently considerably better, however, and
only at the limiting angle of $90^\circ$ is the minimum pressure lower. Had the best of the modified-ellipsoidal forms for zero yaw ($d:3d/8$) been chosen, it is probable that its performance at other angles would have been decidedly worse, for much the same reasons as have been presented for the 4:1 semiellipsoid.

Although the ogival form, of which the 2-caliber is the basis of the last group of diagrams (Plate VIII), has gradually decreased in frequency of appearance, it would seem from the present tests to show the best overall performance through the range investigated. Except for the familiar three-dimensional effect behind the head at $45^\circ$, there is little further about the plotted curves that warrants special comment.

V. Conclusion

If used in conjunction with Bulletin 32, which describes in detail a previous investigation of cavitation and pressure distribution on twenty-odd head forms at zero angle of yaw, the present bulletin will provide a convenient survey of the pressure modifications that occur as eight typical heads are varied in yaw from $0^\circ$ to $90^\circ$. Owing to the difficulties involved in developing the necessary experimental skill and then in directing such a project from a distance, the writer cannot claim for the results the accuracy of those previously presented. On the other hand, the eight plates of experimental data should prove of value even if only their qualitative significance is considered: first, for the instructiveness of the transition from axial symmetry to three-dimensional conditions of flow; second, as an aid in planning instruments for the measurement of velocity and pressure—whether as steady or fluctuating quantities; and, third, as originally intended, in connection with the design of torpedoes and related naval vessels or appendages. To a limited degree, in fact, they may be found to have quantitative as well as qualitative worth.
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Bulletin 33. "Third Decade of Hydraulics at the State University of Iowa," edited by M. C. Boyer, 1949. 84 pages, 8 figures, price $0.50.


Plate VI. 2:1 Semielipoidal Head.

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Plate VII. d/2:d/4 Modified Ellipsoidal Head.