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76-851

Recent Studies of Struts and Foils for High Speed Hydrofoils

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AIAA/SNAME Advanced Marine Vehicles Conference

ARLINGTON, VIRGINIA/SEPTEMBER 20-22, 1976

-- NOTES --

RECENT STUDIES OF STRUTS AND FOILS FOR HIGH-SPEED APPLICATION

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Abstract

A three-year program was undertaken to determine the feasibility of developing a strut-foil system for high-speed operation of hydrofoil craft that would also perform satisfactorily at takeoff and moderate speeds.

Following identification of possible risk areas and design problems, the major objectives and approaches were established. The evaluation included determination of representative hydrodynamic loads and a series of model tests in the areas of hydrodynamic efficiency, cavity stability, side force and ventilation envelop, and strut flutter.

This paper provides highlights of the major portions of the study *together* with the most significant findings.

Introduction

In September 1972, the Naval Material Command (NAVMAT) requested the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) to undertake a three-year program (designated as TAP) to determine the feasiblity of developing a strut-foil system for high-speed operation of hydrofoil craft.

The major objectives of this program were:

1. To identify quantatively the actual technical problems to be encountered and to introduce new approaches to circumvent them.

2. To generate a data base for solving these problems and thus enable selection of a strut/foil system that can operate adequately throughout the entire designed speed range.

3. To recommend improvements in foil efficiency and to indicate other areas requiring further theoretical and experimental studies.

This paper provides highlights of the major portions of the study and presents the most significant findings. Additional information on the program is available in References 1 and 2.

A hydrofoil has two modes of operation: the normal slow-speed hullborne mode and the high-speed foilborne mode. In the foilborne mode, the effectivelift-to-drag ratio (L/D) must be adequate for the intended operation and, at the same time, the craft must be able to fly in a stable, controllable manner with a satisfactory environment for crew to accomplish the required mission.[3]

The successful operation of existing subcavitating hydrofoils (40-50 knots) has been well demonstrated and discussed in Reference 4. Thus far, most foil and strut section shapes used in the U.S. naval craft have been selected from the NACA design literature, e.g., the 16 Series. Experience indicates that it is extremely difficult to avoid cavitation on a subcavitating foil at speeds much above 50 knots at the practical depth of submergence. At speeds greater than this, small bubbles or cavities tend to form on the low pressure stde of the foil. These are detrimental to performance and, as they collapse, are destructive to the foil structure itself.

Extensive studies have been made by governmental, industrial, and institutional organization *to* develop some means of delaying the inception of cavitation on the foil. One innovative approach was developed in the hydrofoil program of the Canadian Navy. A suitable section termed "delay cavitation section" has been designed and demonstrated successfully up to 60 knots in calm water, with angle-of-attack tolerance for rough water operation at 50 knots on the main foil of the 200-ton surface-piercing hydrofoil BRAS D'OR.5

However, as pointed out by Eames and Jones,[5] this is probably the practical limit of the delayed cavitation *regime. At* high speeds, lift coefficients are restricted to unrealistically low values and even at 60 knots the limit on section thickness causes very severe structural problems. If future hydrofoils are to be operable at speeds of 60 to 70 knots or greater, new and more suitable strut and foil configurations must be developed.

Review of Previous High-Speed Hydrofoil Programs

Most earlier investigations have taken two basic approaches to the design of high-speed struts and foils. One involves the use of a fully wetted, base-vented section and the other a supercavitating section. Typical section profiles of subcavitating (streamlined) base-vented and supercavitating foils are given in Figure 1. The choice of one type over another requires tradeoffs among such aspects as hydrodynamic performance and structural strength at design speeds as well as mission requirements of the hydrofoil craft in various sea conditions. A summary review of the major high-speed hydrofoil development programs,1955 through 1972 are available in Reference 6.

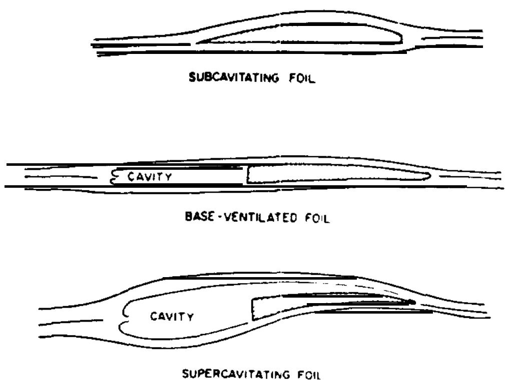

FIGURE 1 - TYPICAL SECTION PROFILES

Early studies on base-vented foils were conducted by Johnson and Rasnick, and by Lang and Daybell, as discussed in Reference 3. Those investigations also provided supporting experimental evidence of good Lift-to-drag ratios. A foil system based on the base-vented principle constituted the demonstration foil during successful testing of the FRESH-l testing craft at 80 knots.

Unfortunately, the tolerance to angle-of-attack variation for cavitation-free operation on this type of foil is relatively limited.[7,8] Because of the proximity of the free-surface, a base-vented foil operated at 'high speeds may be subjected to a phenomenon called "surface ventilation?' The whole upper surface of the foil is then enclosed in a fully ventilated cavity. This will result in a significant reduction in Lift, which in turn, creates a difficult control problem especially at high speeds. Moreover, because of problems related to surface ventilation, the takeoff speed of FRESH-L was 45 knots. Such a high required takeoff speed may not be desirable for an operational naval hydrofoil.

The innovative concept of variable geometry was first introduced by Hydronautics Inc., in the design of Boeing annex foil.[9] The foil was designed with low-drag supercavitating sections and was intended to achieve takeoff in a base-vented mode. The foil wetted area at takeoff (annex wetted) was double the wetted area at cruise (annex not wetted). The annex also provided additional structure at cruise in otherwise unused space. The foil was designed to operate at speeds above 50 knots in supercavitating mode with full ventilation provided from a blunt-based strut. This model was tested in the Boeing High-Speed Test Craft. The six different flow regimes observed over the foil were attributed to the complicated flap geometry. The most pertinent problem during the tests was getting the annex to unwet.[10]

The innovative concept of smooth transition was introduced by Grumman Corporation during the development of the transit foil.[11] The foil has an airfoil section of NACA 16 Series, a thickness to chord ratio of 4 percent, and the strut had a base-vented profile. The purpose of the Grumman effort was to replace the demonstration foil on the FRESH-l by a system designed to operate in a transcavitatfng or partially cavitating flow. The design plan called for the cavity to form first at the wing tips and migrate inward toward the pod as speed increased. The objective of this program was then to achieve a smooth transition as the speed is increased. Because of the hysteresis effect, however, it is unclear whether smooth transition can still be achieved as the craft speed is decreased. In addition to the disadvantage of its thick leading edge, the transit foil section differs greatly from a conventional Low-drag supercavitating profile and this will result in inefficient operation at high speed in full cavity flows.[12]

Experience indicates that it is extremely difficult for a strut of practical size, to avoid cavitation on a subcavitating strut at speeds above 50 knots. Struts with blunt-based sections have been extensively studied in an effort to overcome this cavitation barrier. The basic concept in designing a strut for high-speed application is to achieve a shape which initially has no negative pressure along its chord and which has minimum drag for a given cavity thickness. The minimum drag shape described above is a parabola with a ventilated cavity. It is based on a linearized theory developed by Tulin. This theory was later extended by Johnson and Starley to enable the de-velopment of modified parabolic struts.[13]

Because of the danger that a base-vented strut will be subjected to side ventilation, the possibility of using supercavitating struts for high-speed application has been proposed. Extensive model studies of base-vented parabolic struts, modified parabolic struts, and supercavitating struts were carried out at Aerojet ring channel.[14] The supercavitating sections hold promise of providing struts with high structural strength-to-drag ratios, but unfortunately side forces and moments are inadequate to allow craft control. Accordingly, struts of base-vented sections have been used extensively in past high-speed programs.

Approaches Employed in the Present Program

A single fully submerged foil and a surface-piercing strut were considered. Assumptions included maximum craft design speed of 80 knots and takeoff speed of 35 knots. Possible interference effects from propulsive devices or other strut/foil systems were not considered. The criterion for maximum allowable stress in any member of a strut/foil system was based on the use of HY-130 or, alternatively, 17-4 PH stainless steel.

The selection of strut and foil section profiles was one of the most intricate problems in this study. After a brief review of available literature, it was decided to utilize foils with supercavltating sections and struts with base-vented sections. A data base for the design of strut/foil systems can be generated through a series of theoretical and/or experimental studies. Although the approach established for this program emphasized experimental studies, consideration was also given to adequate theoretical support.

Major emphasis was on the following sub-task areas:

Basic Performance of Strut/Foil Systems

Representative Hydrodynamic Loads

Stability Studies of Foil Cavity

Strut Side Force and Side Ventilation

Hydroelastic Instability Studies

Lift and Drag Characteristics of Strut/Foil Systems

TAP-l Strut/Foil System

A method for designing efficient supercavitating sections was first developed by Tulin and Burkart[15] and was further extended by Johnson to three- and five-term sections.[16] According to that theory, a high concentration of pressure near the trailing edge will give lower cavity drag; then the introduction of an angle of attack or point drag will provide a reasonable cavity thickness for structural strength requirements. This method has been used extensively in designing supercavitating foils.

Dobay and Baker[17] recently showed that the sectional lift-to-drag ratio at constant sectional modulus tends to increase as the center of pressure moves forward. In his recent work on designing supercavitating foils, Parkin[18] reported the same trend. Lift coefficient, cavitation number, and cavity thickness are presented on the basis of structural requirements. This contradiction in demand of the pressure distribution stems from the fact that the efficiency derived by Tulin and Johnson imposes a constraint only on minimizing cavity drag whereas Dobay-Baker and Parkin have introduced another constraint, namely, the structural strength requirement.

Following extensive tradeoff studies between the hydrodynamic efficiency and the structural strength of supercavitating sections (simple bending theory), the foil designated as TAP-l was designed by Baker.[19] A base-vented parabolic strut was selected for the TAP-l foil. The major characteristics of the foil is given in Table 1 and the assembly is shown in Figure 2.

The foil section was designed by using the Wu nonlinear cavity flow theory. The foil sections were then twisted about the wetted trailing edge in the spanwise direction to account for the free surface, strut downwash, and dimensional effects. The design philosophy and the selection of planform, aspect ratio, sweep, and taper ratio are throughly covered in References 17 and 19. The foil was designed to operate in the fully ventilated condition at 80 knots with a designed cavity cavitation number less than 0.05.

TABLE 1

Major Characteristics of TAP-1 Foil

Planform		Foil Section	
Aspect Ratio	2.4	Section Profile	Levi-Civita Two-Term
Taper Ratio	0.5	Leading Edge	Sharp
Sweepback at Midchord	6.42°	Lift Coefficient at 41.15 m/sec	0.137
Annex % of wetted Chord	33%	Thickness-to-Chord Ratio (Maximum)	8.6%

FIGURE 2 - TAP-1 STRUT/FOIL ASSEMBLY

The model was first tested at NASA Aircraft Landing Loads and Traction Facility, an outdoor high-speed towing tank, at full-scale speed (vapor cavitation scale) by Holling, Baker and Rood.[20] This cruise speed test was concerned with those phenomena which could not be measured or represented adequately in a simulated speed facility, e.g., the operational boundaries within which the ventilation flow required on the foil could be maintained (strut choking problem) and the possiblity of vibration on the leading edge vibration (flutter problem). To increase the confidence in predicting full-scale performance from model data, the same model was then tested by Kramer[21] at Lockheed Underwater Missile Facility (LUMP), a controllable pressure tank, under simultaneous vapor (cavitation and Froude scaling. The possible Froude scale effect on foil and strut performance was examined by considering three different model scale ratios λ, the ratio of model size to the conceptual full-scale sizes.

Figures 3a and 3b give some of the test results for the TAP-l foil fitted on a 12-percent parabolic strut. In these figures, the foil was submerged at one-chord depth and the nominal angle of incidence on the foil was 8.4 degrees. The lift coefficients obtained at LUMF were slightly lower than those obtained at NASA. (This same trend was also observed by Waid in his correlation studies of the BuShips parent foil at various test facilities.[22])

Measurements from two pressure tranducers subsequently installed on the upper surface of the TAP-l foil indicated that the cavity cavitation numbers measured at LUMF were lower than those measured at NASA. Aside from the possible Froude effect, the differences in cavitation number may partly explain the discrepancy between the data obtained at these two facilities.

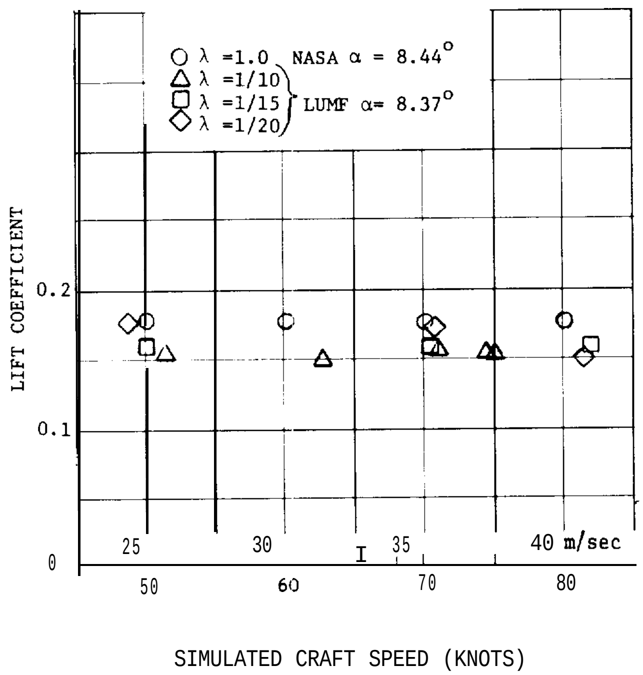

FIGURE 3a - LIFT COEFFICIENT AT ONE-CHORD SUBMERGENCE

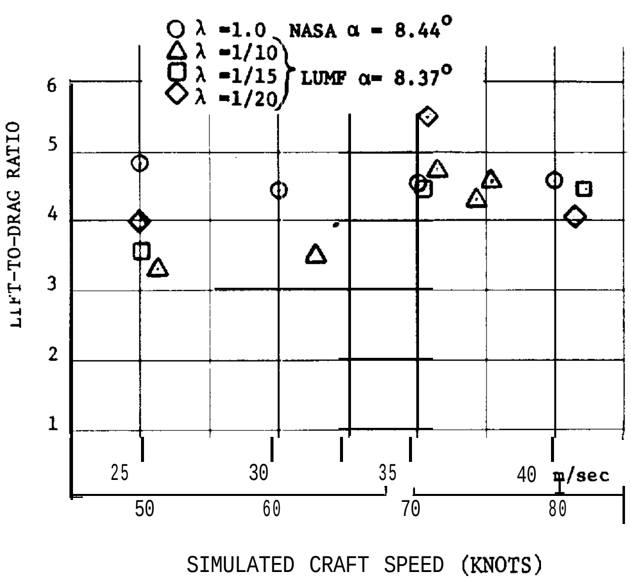

FIGURE 3b - LIFT/DRAG RATIO AT ONE-CHORD SUBMERGENCE

FIGURE 3 - TEST RESULTS FOR TAP-l FOIL FITTED ON A 12-PERCENT PARABOLIC STRUT

The L/D ratios obtained at the two facilities were quite scattered for simulated craft speeds of 50 to 60 knots, but the agreement was reasonably good at simulated speeds of 70 to 80 knots (low vapor cavitation numbers). The maximum L/D measured at NASA in full cavit flow at one-chord depth of submergence was 6.6[50]. The measured design lift coefficient was much lower than the value predicted by two-dimensional theory.

The section shape of the TAP-l foil was designed with a sharp leading edge. See Figure 4 for a comparison of the leading edge thicknesses of TAP-l and the parent foil; the similarity of these two profiles is obvious. Yet, there was severe leading edge vibration on the BuShips parent foil even at speeds of 70 knots[23] and no visible vibration was indicated in the motion pictures of TAP-l foil even at 80 knots. The parent foil has a rectangular planform and no sweep whereas TAP-l is tapered with 21.5 degrees sweep at the leading edge. Presumably, the difference in vibrations is partly accounted for by the leading sweepback and partly by the reduced aspect ratio of TAP-l.

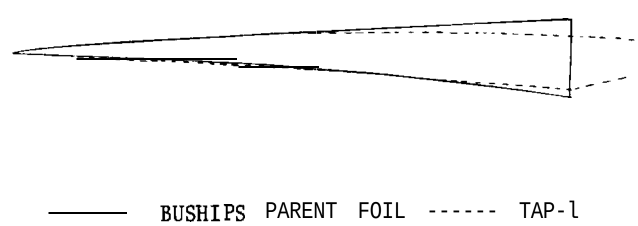

FIGURE 4 - COMPARISON OF FOIL SECTIONS OF TAP-l AND BUSHIPS PARENT FOIL

The effectiveness of a flap for unsteady load control had been well demonstrated on existing naval hydrofoil craft. It had also been observed that a flap can be used effectively as a high-lift device. Accordingly, takeoff experiments on the TAP-l system were carried out to determine the most favorable combination of flap angle and incidence angle for takeoff in supercavitating and base-vented flow conditions. The experiments were conducted at DTNSRDC Langley Tank 1 by Holling.[24] The maximum L/D obtainable at the design takeoff lift was around 3 to 4.

A successful takeoff must be achieved before a hydrofoil can begin to operate in the foilborne mode. For hydrofoils with a wide speed range, the problem during takeoff may be propulsion rather than powering. If the drag is too large, thrust may be inadequate to accelerate the craft. Experience suggests that takeoff may be difficult for a high-speed hydrofoil fitted with the TAP-l strut/foil system. Accordingly a new strut/foil system was aabsequently developed, namely, TAP-2.

TAP-2 Strut/Foil System

In the design phase of the TAP-2 strut/foil system, attention was focused on high-speed cruising at 60 to 70 knots. Because of the possibility of difficulty at takeoff with the TAP-1 foil, improvement of takeoff capability received major emphasis in the design of TAP-2. The total craft L/D ratios of existing subcavitating hydrofoils are generally 10 to 12 at takeoff. A takeoff speed of around 30 knots is not a problem for present-day subcavitating hydrofoils. It was decided that if at all possible, the TAP-2 foil should be able to take off in the fully wetted flow mode. At high speeds (above 50 knots,), the foil would be operated in a fully cavitating flow regime. In this design effort by Baker,[25] the high-speed cruise range at 60 knots was considered the normal mode of fast operation. The burst-speed capability above 60 knots could be achieved by operating foils with a lower surface spoiler to reduce their lifting area.

The supercavitating section was designed by using the Furuya two-dimensional nonlinear cavity flow program including the free surface effect.[26] Recall that the TAP-1 foil was designed with the lower wetted surface twisted along the spanwise direction. It was later pointed out by Baker that this approach would result in a large drag component. Accordingly, for TAP-2, only the upper surface was rotated to accommodate the three-dimensional effect. The structural design was based on simple bending theory at 60 knots. At takeoff the foil section including the annex part was designed in a streamlined profile. The design philosophy of the TAP-2 foil is given in Reference 25. At takeoff, the strut was of an NACA 16-012 section and at high-speed operation it was converted to a base-vented section by two split flaps. The major characteristics of TAP-2 are given in Table 2 and the assembly is shown in Figure 5.

TABLE 2

Major Characteristics of TAP-2 Foil

Planform		Foil Section	
Aspect Ratio	5	Section Profile	Circular Arc
Taper Ratio	0.5	Leading Edge	Ellipse
Sweepback at Midchord	7.5°	Lift Coefficient at 30.86 m/sec	0.2
Annex % of Wetted Chord	20%	Thickness-to-Chord Ratio (Maximum)	7-7.5%

The TAP-2 foil was designed to operate in a supercavitating condition during high-speed operation. The model was tested at LUMP[21] with model scale ratios of $\lambda = 1/10$, $1/15$, and $1/20$. Results are shown in Figures 6a and 6b $\lambda = 1/10$, and d/c = 0.5, 1.0 and 2.0; c and d respectively represent the foil mean chord and the depth of submergence. Flow observations from motion pictures suggest that transition from fully wetted flow to full ventilation of the upper surface of the foil occurs around a pitch angle of 2 degrees. Because of the small leading edge radius, the exact location of the cavity

FIGURE 5 - TAP-2 STRUT/FOIL ASSEMBLY

separation point was not so well defined as that of a sharp leading edge foil. This is an area that warrants further studies. The lift curve in Figure 6a suggests that the foil achieved full ventilation around 1.9 and 2.5 degrees at d/c = 0.5 and 1.0, respectively. The maximum measured L/D in fully cavitated flows was approximately 9 to 10 at lone-chord depth of submergence. The problem of possible foil rewetting on the annex part has not been investigated.

The effect of foil submergence on the lift coefficients is seen to be minimal in fully cavitated flows. However, the L/D ratios change significantly with the depth of submergence. The improvement in the strut/foil efficiency at shallow submergence may be due partly to the reduction in strut drag and partly to the reduction in cavity cavitation number on the foil and strut downwash effect. The same trend was also found in test results for the TAP-1 foil, the Boeing annex foil, and the BuShips parent foil. On the other hand, if a supercavitating foil is designed to operate at deeper submergence, a degradation in L/D will result.

A conventional subcavitating hydrofoil is generally operated around one-chord depth of submergence to minimize the free-surface effect. However, the free-surface effect on lift coefficient of a supercavitating foil is relatively mild. In addition, the upper surface of a supercavitating foil is already fully ventilated. The undesirable phenomena of upper surface cavitation and ventilation on subcavitating and fully wetted base-vented foils are not problems for supercavitating foils. It is thus of great importance to explore the possibility of operating a supercavitating foil at small value of d/c, especially in the cases of big hydrofoils, so that high L/D ratios can be achieved. Of course, the possible effects of craft performance due to orbital velocities in waves and directional stability due to the reduction in strut wetted area must be carefully explored.

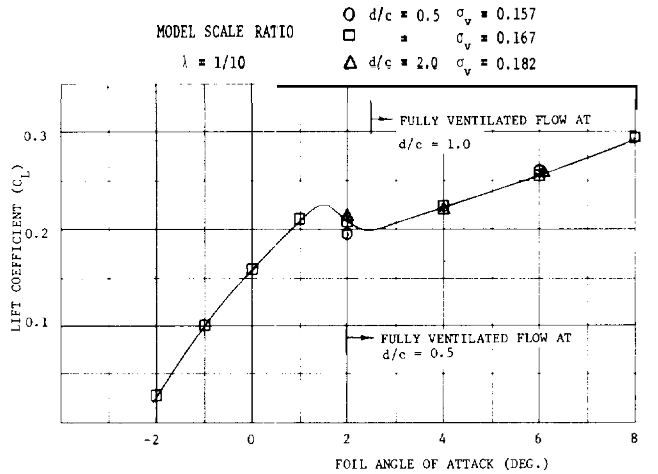

FIGURE 6a - LIFT-COEFFICIENT AT ONE-CHORD SUBMERGENCE

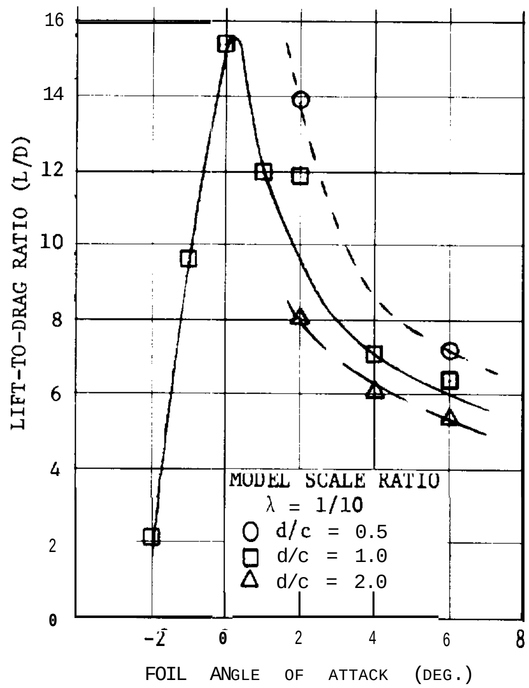

FIGURE 6b - LIFT/DRAG RATIO AT ONE-CHORD SUBMERGENCE

FIGURE 6 - TEST RESULT'S FOR TAP-2 FOIL

Accordingly the supercavitating TAP-2 foil was designed to operate in a subcavitating condition at takeoff. The experiments were conducted at DTNSRDC Langley Tank 1 by Holling.[27] At the takeoff speed of 35 knots and foil submergence of d/c = 2.C and 3.0, the maximum measured L/D of the strut/foil system was 14.25. In the takeoff study, the mean chord C was based on the wetted section. As seen in Figure 7, the measured L/D at the designed lift of C_L = 0.49 was approximately 13.0. As long as the strut and foil remain fully wetted or at most only partially cavitated around the leading edge, the hydrodynamic efficiency of strut/foil systems compatible to the existing subcavitating hydrofoils can be expected. A successful takeoff with the TAP-Z strut/foil system can be anticipated.

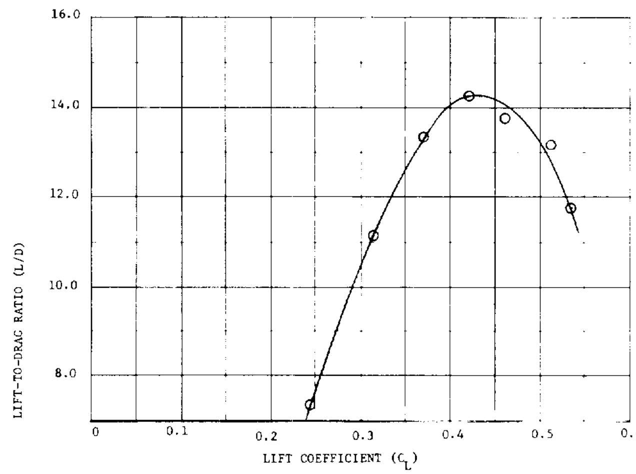

FIGURE 7 - LIFT-TO-DRAG RATIO OF TAP-2 SYSTEM AS A FUNCTION OF LIFT COEFFICIENT FOR SPEED OF 18 m/sec AT d/c = 3.0

Development of Strut and Foil Design Methods

Although the major' effort in this project was experimentally oriented, some parallel theoretical effort was made in support of the program.

Validation Study of "Mixed Foil" Concept

A reasonable L/D can be achieved for a supercavitating foil if' the foil is operated at the design condition. However, the capability to operate efficiently at moderate speeds may be equally as important in the development of a high-speed hydrofoil craft. Unfortunately, the supercavitating foils that enable hydrofoils to operate at high speeds make for very inefficient operation at moderate speeds. The difficulty stems from the different requirements on lift coefficient C_L at moderate and at high speeds. The increase in the drag coefficient C_D of a supercavitating foil is generally much higher than that of the lift coefficient C_L. This will result in poor hydrodynamic efficiency during moderate-speed operation. The consequence is a reduction in the available range of foilborne operation.

As already indicated, when either fully wetted base-vented sections or supercavitating sections are operated with cavity flows, the maximum attainable hydrodynamic efficiencies are inherently lower than for conventional subcavitating strut/foil systems at speeds less than 50 knots. The performance of a subcavitating foil on naval hydrofoils equipped with streamlined foils and struts had already been demonstrated at speeds up to 50 knots. It had also been observed that takeoff speeds in the neighborhood of 30 knots was not a problem for present-day, moderate speed hydrofoils. The L/D ratios of strut/foil systems for such a moderate-speed hydrofoil are generally 10 to 12 at takeoff and greater than 15 in the foilborne condition. To circumvent the takeoff problem as observed in the TAP-1 foil and to increase the range of foilborne operation, it is highly desirable for a high-speed hydrofoil to have the capability to cruise at moderate speeds and to takeoff efficiently in subcavitating modes.

To achieve that goal, a new design concept was introduced--the mixed foil and pseudoblunt-based strut. A mixed foil is a streamlined hydrofoil equipped with a flap or other device which can be activated above a certain speed to change the flow around the foil into a supercavitating flow. At takeoff and at moderate speeds, a mixed foil is operated as a subcavitating foil; at high speeds, it is operated as a supercavitating foil. A pseudobluat-based strut is a streamlined strut equipped with a flap or other devices which can be activated above a certain speed to become a base-vented strut. Sketches of this mixed foil and pseudoblunt-based strut are given in Figure 8.

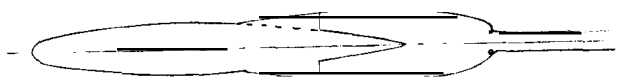

FIGURE 8a - PSEUDOBLUNT-BASED STRUT

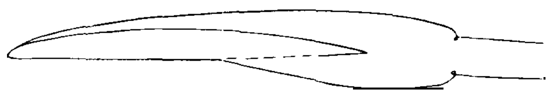

FIGURE 8b - MIXED FOIL

FIGURE 8 - THE NEW DESIGN CONCEPT OF MIXED FOIL

Based on a series of two-dimensional model tests, a theoretical hydrodynamic validation study of the foil concept was carried out by Wang and Shen[28] on two planoconvex section hydrofoils and a pseudoblunt-based strut. One of the main reasons for chocsing a plenoconvex section as a basic foil in this study was to serve as an example. However, some similarities between the Canadian BRAS D'OR delayed cavitation section profile and a planoconvex section profile are noticed in Figure 9.

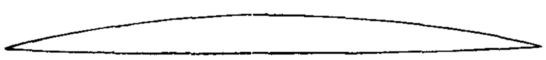

FIG 9a DELAYED CAVITATION SECTION

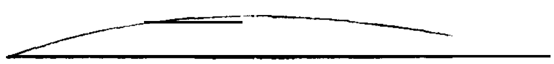

FIG 9b PLANO-CONVEX SECTION

FIGURE 9 - COMPARISON OF FOIL SECTIONS OF DELAYED CAVITATION SECTION AND PLANO-CONVEX SECTION

The calculated L/D ratio of this strut/foil system was found to be around 13 to 14 at takeoff and about 18 cruising at 45 knots. At high-speed (80 knots) there was a 50 percent reduction in foil areas. The foil with lo-percent thickness was operated in a supercavitating condition with a calculated L/D of 7.6 at d/c = 1.0. These theoretical studies suggest that a reasonable good L/D can be achieved at cruising high-speed and that hydrodynamic efficiency of a mixed foil at cruising moderate-speed is similar to that of existing hydrofoils.

Supercavitating Section Design Method

Possible hydrodynamic trends for use in tradeoff studies for the preliminary design of fully cavitating hydrofoil sections were theoretically investigated by Parkin.[18] Hydrodynamic data were obtained from inverse calculations based on two-dimensional, linearized, cavity-flow theory. Supplementary data were also calculated from the direct problem of linearized cavity-flow theory in order to show off-design performance trends and to assess the effects of cavity-foil interference on the operating range of selected profiles. Results have been published on a parametric study of the effects of design cavitation number, lift coefficient, cavity thickness, and pressure distribution shape on hydrofoil section performance and geometry.

Mixed-Foil Study

A linearized mixed foil theory has been developed by Wang and Shen[29] for two-dimensional foils in an unbounded fluid. The lower surface profile is specified in terms of high-speed superventilating mode performance and the upper surface pressure distribution is specified in *terms* of sea-state requirements for moderate speeds. The foil section of streamlined profile is then computed from the theory.

Unsteady Supercavitating Flow Theory

A hydrofoil is operated in the proximity of the free surface. A theory has been developed by Parkin[30] for determining the response of a hydrofoil to streamwise sinusoidal and sharp-edged *gusts* at zero cavitation number.

Three-Dimensional Theories for Surface-Piercing Struts

Yim[31] has analyzed flows of ventilating or cavitating struts numerically by using a three-dimensional mathematical mode. The strut drag and the possible interference effect of a strut on the foil performance (strut downwash effect) have been computed.

Representative Hydrodynamic Loads

As the desired operating speed for the hydrofoil is increased, the design of the craft becomes more critical in terms of structural weight and payload requirements. The hydrodynamic efficiency L/D of a supercavitating foil is relatively sensitive to foil thickness. Inasmuch as thin foil sections are desirable to enable high hydrodynamic efficiencies to be attained by supercavitating foils, high strength materials and advanced methods for stress analysis are in order.

Significant progress has recently been made in the development of advanced composite materials which possess high strength, high modulus, and low density. The application of such composites may result in a substantial weight saving. However, this subject is beyond the scope of this paper. Instead, the attention is directed (a) to the establishment of possible representative hydrodynamic loads to 'be encountered and (b) to methods for stress calculation.

The limit load approach presently employed for Navy subcavitating hydrofoil ship design was adopted in this study. Four critical loading conditions (representative hydrodynamic loads) anticipated in service were specified; see Table 3. Detailed loads corresponding to each of the loading conditions were calculated by Hoyt et al[32]. The loads so determined are designated limit loads, These, in turn, are multiplied by specified factors of safety to obtain yield loads and ultimate loads.

TABLE 3

Design Loading Conditions

Condition	Description
Maximum Lift at Maximum Speed	2.5 Factors of Lift at Maximum Speed
Maximum Lift at Maximum Elevator Deflection	2.5 Factors of Lift at Maximum Elevator Deflection
Maneuvering in High Seas	Maximum Strut Side Force Combined with 60%-40% Lift Distribution at 1.5 Factors of Lift
Foil Re-Entry	1.0 Factor of Lift on One Semi-Span Only

The conceptual design of the TAP-l foil as carried out by Clark[32] was based on the representative hydrodynamic loads so developed. The foil leading edge structure is solid from the leading edge back to approximately 30-percent chord point. Because of the relatively thin foil section in this area, use of a solid section was considered reasonable from the viewpoint of structural weight. Because a Locally solid section was employed, no difficulty was experienced in carrying chordwise bending loads back to the main structural box. Spanwise bending stresses are maximum immediately outboard of the machined forging which forms the center of the foil. Again, no significant difficulties were encountered in withstanding the applied loads with reasonable structural propositions. The conceptual structural design of TAP-Z has not been undertaken.

Because simple bending theory is commonly used to provide estimates of required structural proportions, calculations of the more exact finite element stresses were compared to values estimated by this simplified approach. This comparison was for leading edge and foil root bending stresses of TAP-1 foil.32333 The chordwise stresses calculated by simple bending theory were found to be larger than those derived from the finite element analysis, Increasingly so the further away from the leading edge. Thus simple bending theory gives a conservative estimate of the strength of the leading edge of the foil. In the case of spanwise stresses, simple bending theory exaggerates the stresses at the trailing edge, where the section thickness is greatest. On the other hand, the maximum stresses obtained by the two approaches are fairly similar. An example is shown in Figure 10 for the foil spanwise bending stress at 0.16 span. This subject is discussed in greater detail in Reference-32.

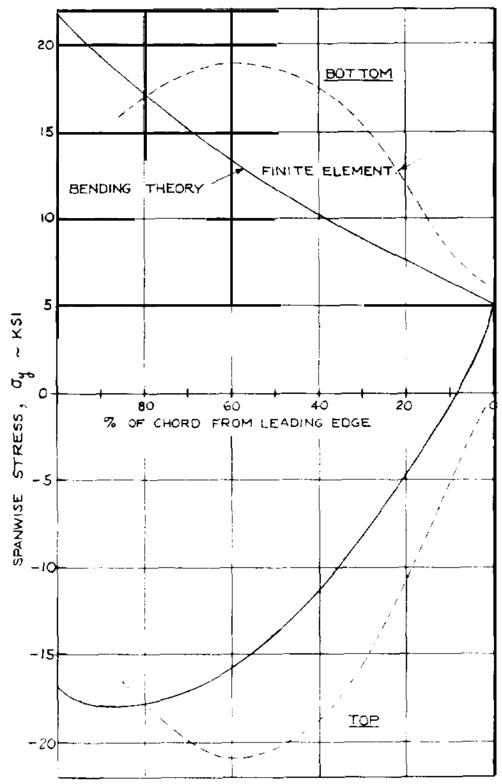

FIGURE 10 FOIL SPANWISE BENDING STRESS AT 0.16 SPAN

If a mixed foil is employed, the control systems may have to be relatively complex compared to those of existing subcavitating hydrofoils As an example, control systems of the Boeing annex foil include two lower surface flaps for takeoff and high-speed lift control and one upper surface spoiler for the lift reduction. The possibility of constructing a prototype of the Boeing annex foil had been demonstrated in a feasibility study by Cohn and Ross.[34] However, efforts must be made to minimize or simplify the required control devices.

Stability Studies of Foil Cavity

Calm Water

The hydrodynamic performance of a super-cavitating foil depends significantly on cavity cavitation number, σ_c. The cavity pressure on a fully cavitated flow falls between ambient pressure and vapor pressure, namely, $0 \leq \sigma_c \leq \sigma_v$. A recent numerical calculation by Baker showed that if the stress level on the foil was considered, the L/D was higher for TAP-l when a lower cavitation number was used. This result favors the use of low σ_c for the foil design with the cavity ventilated.

The foil cavity can be ventilated (a) from the surface through the cavity wake trailing behind the base-vented strut, (b) from the free surface through the foil surface ventilation, and (c) by forced ventilation through an internal piping system. The first of these approaches is simple and possibly the most economic way to ventilate the foil cavity. However, strut choking[23, 35] (i.e., blocked air path from the free surface) on a supercavitating foil with a blunt-based section has been observed in high-speed model tests. This will result in an unpredictable lift force on the foil.

Extensive studies of foil cavity pressure versus strut profiles were conducted on TAP-l and TAP-2 at NASA and LUMP facilities. The measured cavity pressure on the TAP-l foil at NASA ($\lambda = 1$) is given in Figure 11 for 12 and 18 percent parabolic struts at one-chord depth of submergence. The sudden cut-off of ventilation air above certain speeds, noted in model tests of the BuShips parent foil, was not observed on TAP-l. Rather, there was a gradual and linear decrease with speed of the cavity pressure. This same trend has also been observed by Wadlin.[36] As expected, foil ventilation was more complete with an 18 than with a 12-percent parabolic strut. However, a slight degradation in L/D was noticed with the thicker strut. Thus a tradeoff is required in order to select the strut size.

Full ventilation on the TAP-l foil was not achieved with these two struts. Experiments by Wadlin indicated that the spray region at the intersection of the strut with the free surface tends to close the air passage created behind the blunt-based strut at higher speeds and deeper depth of submergence. Tulin and Johnson[9] mentioned the forced injection of air into the spray region as one way to prevent spray closure. In the present project, we followed the Wadlin suggestion and installed strut spray wedges on the strut. These spray wedges enabled full ventilation on the TAP-1 to be achieved even at a carriage speed of 90 knots. This achievement was accompanied by additional strut spray and cavity drags, in turn, there was a noticeable reduction of L/D.[20]

LUMF explored possible Froude scale effects on foil ventilation of the TAP-1 model.[21] As seen in Figure 11, the cavity cavitation numbers measured at LUMF and NASA facilities were quite compatible at low but not at high simulated craft speeds. The degree of foil ventilation depends on the amount of air supplied and entrained. It may be worth mentioning that the parameter "air

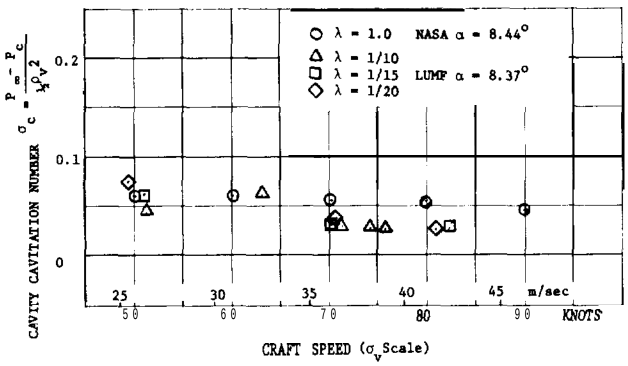

FIGURE 11a - FOIL WITH 12-PERCENT STRUT

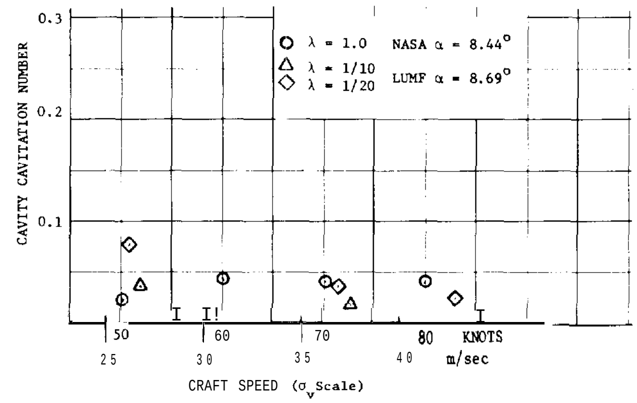

FIGURE 11b - FOIL WITH 18-PERCENT STRUT

FIGURE 11 - VENTILATION CHARACTERISTICS OF TAP-l AT ONE-CHORD SUBMERGENCE

density ratio" must be taken into consideration when comparing NASA and LUMF studies of foil ventilation.[37]

Two types of strut spray wedges were installed on TAP-2 pseudoblunt-based strut and tested at LUMF. One wedge, designated as wedge A, was straight, i.e., it had a uniform cross section of 24-percent thickness. The other wedge, designated as wedge B, was tapered to a smaller cross section at the lower end. Full ventilation on the foil was observed with either type of strut spray wedge. The comparison of L/D with both wedges suggests that the overall efficiency of wedge B is higher[21]. The information generated in this program provides a base for tradeoff studies between the efficiency and the degree of foil ventilation for future strut/foil designs.

In Waves

In investigating possible sources of unsteady loads to be encountered in waves by a high-speed hydrofoil fitted with super-cavitating foils, we can simplify matters by considering only pitch and heave motions. The effective angles of attack on the foil exhibit fluctuations ($\Delta\alpha$) due to pitch, heave, and water particle motion. The force characteristics on the foil may also be affected by fluctuations in the foil depth of submergence (ΔH). For a supercavitating foil, the force characteristics are also a function of cavity cavitation number ($\Delta \sigma_c$) and thus also may exhibit fluctuations in random seas.

The lift slope $\partial C_L/\partial \alpha$ of a two-dimensional subcavitating foil (flat plate) is approximately 2π whereas that of a supercavitating foil is $\pi/2$. This means that the CL of **fully** cavitating hydrofoils is quite insensitive to variations in small angles of attack. In addition, for a given sea state, the induced angle of attack due to wave orbital velocity is reduced linearly as craft speed is increased. Similar to a subcavitating foil, the lift slope of a supercavitating foil can be reduced by a finite aspect ratio wing. Hence, when the flow is kept fully cavitating, the lift fluctuation in waves due to $(\partial C_L/\partial \alpha) \Delta a$ is likely to be much smaller than that of a subcavitating foil. In the second term, if a foil is designed with a proper camber, the lift fluctuation due to $(\partial C_L/\partial H)\ \Delta H$ at the normal depth of submergence is likely to be small and negligible.

The unsteady force arises from the third term is a unique characteristic of supercavitating foils. By way of example, Figure 12 indicates the effect of cavitation number on the lift coefficient of a supercavitating foil based on a nonlinear cavity flow theory[38]. For a given incidence angle, the lift slope $\partial C_L/\partial \sigma_c$ is seen to be smallest at $\sigma_c = 0$. Fortunately, this demand is the same as for the design of eff-icient supercavitating foils. For **a** hydrofoil operated in the proximity of the free surface, the cavity pressure on a supercavitating foil falls between the vapor pressure and the atmospheric pressure. It is known that a significant change in lift coefficient will be observed if the pressure inside the cavity fluctuates. Consequently, if the cavity pressure in a supercavitating foil can be controlled, a high-speed hydrofoil should ride smoother in waves.

Experimental studies on TAP-l and TAP-2 systems indicate that an almost constant value of cavity cavitation number can be maintained in calm water up to speeds of 80 knots at the normal depth of submergence. No strut choking i.e., a sudden variation in the cavity cavitation number has been observed in this series of model tests.

To determine the magnitude of the unsteady lift and drag forces and the stability of the cavity under waves Conolly[39] tested two supercavitating foils in calm water and in waves with and without forced ventilation. The first model was a five-term camber supercavitating foil of aspect ratio 3 with rectangular planform, and the second was a two-term camber of aspect ratio 3 and 0.5 taper ratio. The strut used in these experiments had an NACA streamlined section. Most of the tests were conducted at speeds of 18.3 to 24.4 **m/sec.** The major findings of these experiments were as follows:

(1) When a supercavitating foil was run in waves **at cavitating** speeds within ¼ chord of the water surface, sooner or later it hits a large disturbance. This caused the cavity to spring open

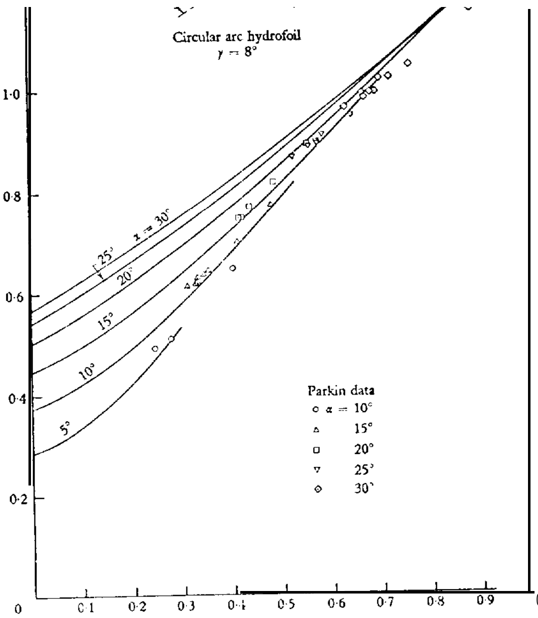

FIGURE 12 - Variation of C_L with σ for a circular arc hydrofoil at incidence α.

to the atmosphere, and the foil was then in a superventilated condition. This phenomena was termed hyperventilation by Conolly. It was called the planning condition in early works.[40] See Figure 13 for a top view of the foil in a superventilated condition. The cavity on the foil was smooth and transparent.

FIGURE 13 - TOP VIEW OF HYDROFOIL IN A SUI?ERVENTILATED CONDITION IN WAVES

(2) Once the superventilated condition was generated, the ventilated condition was maintained to depths of submergence lower than 1 1/2 to 2 chords even through the speed may have been reduced to that which

originally formed the cavity on the foil.

(3) On broaching and reentering the water in a wave condition, the foil immediately picked up full lift; no significant change of lift with depth of submergence was observed.

(4) Within the range of tests, the second foil with different planform, sweep, and cross section seemed to produce superventilation at the same condition as the first foil in waves.

Further studies on this subject were carried out by Stahl and Zarnick[41] with combined natural and forced ventilation in regular waves. Conditions for natural ventilation (ventilation boundary) were enhanced by the addition of wedges to the after end of the strut (pseudo-blunt-based strut). Once a full cavity was developed, the mean lift coefficient was dependent only on the mean cavitation number; within the range examined, it was independent of wave length, foil speed, and foil depth. The mean drag data also appeared to be a function of cavitation number; however, compared to mean drag in calm water, values were higher in head waves and lower in following waves. In general, the oscillatory lift and drag of the foil followed the same behavior as the mean cavitation number. The possibility of annex rewetting in waves was not examined. Further studies are needed to establish the ventilation boundary of the foil cavity.

Strut Side Forces and Side Ventilation

The struts of a high-speed hydrofoil must provide adequate size, length, structuralstrength, and predictable side force characteristics with the lowest possible resistance. In addition, the struts must provide a sufficient air path from the atmosphere to vent the foil if a superventilated condition is desired.

Lateral stability and control of high-speed hydrofoils are generally derived from the supporting struts. However, the struts may suddenly experience side ventilation when the craft is operating at high speeds in a seaway or performing high-speed turning maneuvers. This ventilation phenomenon causes a significant change in the flow field and in the forces on the struts. The capability to maintain the craft in a steady turn or on a straight course in waves will be greatly degraded or restricted due to strut side ventilation. Because of the flow about a surface-piercing strut is so complex,, a reliable mathematical theory is not yet available for predicting the side force characteristics and the inception of ventilation on struts. In current practice, small-scale models are generally used to provide information for full-scale prediction.

General scaling parameters governing strut side ventilation have been discussed by Morgan[42] and further examined by Rothblum,[43] and by Shen and Rood.[44] Experience has shown that separated flow regions will occur for foil shapes in geometrically similar locations provided $R_e > 10^6$.

As the acceleration due to pressure differences become large compared to the acceleration of gravity, vapor cavitation number scaling becomes more important than Froude scaling. Two base-vented parabolic struts of 12- and 18-percent thickness-to-chord ratios were tested at the NASA and the 18 percent strut was tested at LUMF. The struts were fitted on the TAP-l supercavitating foil.

The aforementioned studies of parabolic struts by NASA and LUMP included determination of side force characteristics.[20,21] Values for side force coefficients and ventilation boundaries obtained in the two studies were in reasonable agreement. For example, see Figure 14 which gives side force characteristics of an 18-percent parabolic strut at a craft speed of 70 knots and with the foil' submerged at one-chord depth. In this figure, C is the chord of strut and D is the depth of submergence. For the foil operated at a one-chord submergence, the measured ventilation inception angles of parabolic struts at 80 knots were found to be around 3.25 and 2.5 degrees for the foil in the ventilated and wetted conditions, respectively. This small range of allowable yaw angles at 80 knots raised concern about possible limitations of craft control in beam seas and craft maneuvering characteristics at high speeds.

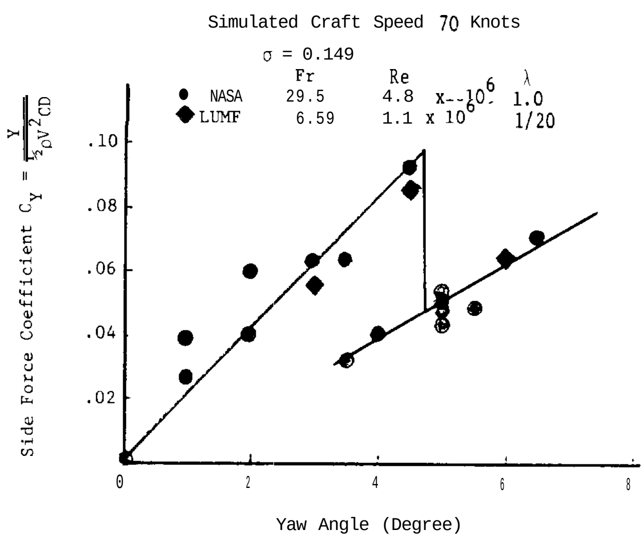

FIGURE 14 - SIDE FORCE COEFFICIENT VERSUS YAW ANGLE (18% PARABOLIC STRUT)

A series of expe-riments on the pseudoblunt-based strut fitted with the TAP-2 supercavitating foil was subsequently carried out at LUMF for simulated full-scale craft speeds of 50 to 80 knots. With the foil operating at one-chord submergence, the ventilation angle measured on the TAP-2 pseudoblunt-based strut at 80 knots was approximately 4.5 to 5 deg :Eor the foils in the ventilated condition. A significant improvement in ventilation sideslip angle was observed for the TAP-2 pseudoblunt-based strut.

Rood used an existing six-degrees- of- freedom computerized simulation to study turning characteristics for an 80 knot hydrofoil in coordinated turns. The automatic control system was the same as used in the FRESH-1 80-knot craft with some modification to the gains. The report by Rood[44] discusses achievable craft turning rates and turning diameters at various operational conditions in calm water and waves, His simulated result indicates that reasonable maneuverability can be anticipated for high-speed hydrofoils fitted with supercavitating foils and blunt-based strut. In this study, the gains of control system were assumed to be constant. Consequently, operation of the craft at other than design condition produced turns that were combinations of both flat and coordinated turns in which substantial yaw angles were produced on the struts.. However, fully coordinated turns can be achieved at all speeds by altering the gains with speed. This approach was not examined in this program.

Although the directional stability of a hydrofoil craft can be enhanced by the proper design of an automatic control system, it may be desirable to "build in" reasonable directional stability for the craft per se.. Within the range of tests, the measured side force slope of the TAP-2 pseudoblunt-based strut was found to be almost twice that of the TAP-l parabolic strut. The possible improvements in maneuverability and control of a hydrofoil craft fitted with a pseudoblunt-based strut are likely to be realized with a higher penalty in drag than that of a parabolic strut. A careful tradeoff between craft maneuverability and control will be required in order to select a strut profile that can minimize the drag penalty and retain sufficient air passage to ventilate the foil cavity.

Hydroelastic Instability Studies

Flutter and divergence problems (i.e., hydroelastic instability) played a very crucial role in the early stage of airplane development. Although flutter has not actually been experienced by existing hydrofoils, the question naturally arises as to whether it will be present in a high-speed hydrofoil. This subject has been well discussed in a review report by Abramson, Chu, and Irick.[46]

Conventional supercavitating foils designed with a sharp leading edge have experienced severe leading edge vibration or leading edge flutter. This was observed in model tests of the BuShips parent foil in the NASA high-speed towing tank even at carriage speeds of 60 to 70 knots. Accordingly, leading edge flutter was one of the potential problems considered in the design of TAP-l foil. No leading edge flutter was observed in tests of TAP-l at 80 knots, and none has been reported for tests of the Boeing annex foil at 80 knots. Because of the significant relationship between the hydrodynamic efficiency of a supercavitating foil and the thickness of its leading edge,26 naval architects obviously aim at a thin leading edge in the interest of foil efficiency. It is important, therefore, that consideration be given to leading edge flutter in developing a design criterion.

Available theories and experimental studies indicate that the divergence problem (static) of a supercavitating foil can be avaided by employing a moderate sweepback of the wing.[47] It had been hoped to investigate the possibility of hydroeleastic instability in supercavitating foils subjected to two degrees of freedom in bending and twisting along and about the elastic axis, but that was not possible in this program because of funding limitations. However, this subject has recently been studied by Liu and Caspar.[48]

Besch and Liu[47] analyzed a large body of experimental and theoretical flutter results to determine significant characteristics for hydrofoil struts. Strut/foil systems of the inverted-T configuration that is typical of full-scale hydrofoil craft appear to undergo either bending flutter or torsional flutter, depending on pod and foil characteristics. A parametric survey of strut flutter was subsequently carried out by Besch and Rood.[49] The hydroelastic design of subcavitating and cavitating hydrofoil strut systems to avoid flutter and divergence was studied by Besch and Liu.[47] Their evaluation included the effects on hydrodynamic instability of changing system intertia, elastic stiffness, and structural damping. They concluded that struts with blunt-based profiles appear to undergo flutter in the same mode as struts with subcavitating airfoil shaped profiles but at different speeds.

As the desired operating speed for the hydrofoil is increased, the design of the craft becomes more critical to the structural weight and payload requirements. The FRESH-1 demonstration foil had been tested at 80 knots without the appearance of strut flutter. A kinematically scaled strut flutter model of Grumman transit foil also indicated no strut flutter up to 80 knots.[50] However, these struts were built with relatively high elastic properties. If this type of strut is used for a pratical size hydrofoil, the weight penalty may not be small.

Besch[50] has compiled hydrodynamic and structural parameters for the T-foils on six full-scale naval hydrofoils. The results were utilized in the design of the kinematically scaled strut flutter model (designated as TAP flutter model) of a full-scale ventilated strut/pod/foil system. The selection of the TAP flutter model was based on several requirements; among them was the need for practical design for use at very high speeds. The least stable among the strut/pod/foil configurations that possibly might be used on a prototype craft are the ones that should be studied. Construction of a full-scale prototype of the system had to be feasible by using conventional construction techniques. This was guaranteed for the prototype by using existing hydrofoil systems to derive geometric, inertial , and elastic characteristics for the TAP system. Slight modifications were made in the interest of achieving greater stability, however. The design philosophy of this model has been discussed by Besch.[50] Geometric parameters for the TAP system and several prototype hydrofoil system are given in TABLE 4 and the flutter model is shown in Figure 15.

The TAP flutter model was first excited in water and in air to obtain vibration modes and frequency characteristics. In a

TABLE 4

Comparison of Geometrical Parameters for TAP System and Several Prototype Systems

Strut	TAP Model	PCH (Mod 1) Forward	PGH-1 Tail	PHM Forward	AGEH Tail	Denison Tail	AGEH Main
c, m.	0.15	1.30	1.52	1.69	1.83	2.39*	3.58
L/C	3.23	2.54	3.0	3.31	3.86	2.79	2.33
Λ, deg **	10.0	0	0	6.3	0	0	0
Profile	Parabolic	NACA 16	NACA 16	NACA 16	NACA 16	Blunt base	NACA 16
Thickness	12-20%	12-20%	10-15%	12-27%	10-25%	4-18%	10-20%
Propulsion Pod							
Length/c	2.0		2.79			2.4	2.28
Fineness Ratio	6.3:1		8.5:1			7.5:1	6.6:1
Fairing Pod							
Length/c	2.0	1.88		2.37	2.17	•	
Fineness Ratio	8.1:1	7.1:1	•	6.3:1	5.2:1	•	
Foil							
c_{foil}(root)/c	1.25	1.24	0.78	1.40	1.14	0.87	1.13
AR	2.4	6.1	5.5	5.5	3.0	2.23	3.0
Λ, deg..	14.5	15.0	12.15	11.04	35.2	11.4	35.2
Taper Ratio	0.50	0.25	0.30	0.30	0.30	0.38	0.30

'chord length at 3/4-span
**Sweep Angle of quarter chord

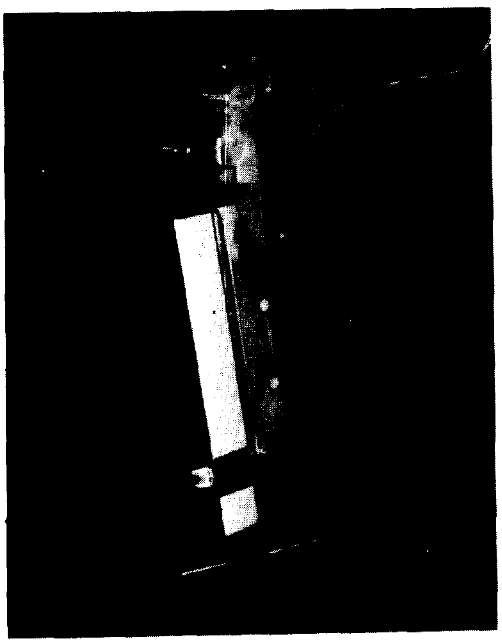

FIGURE 15 - TAP FLUTTER MODEL

subsequent experiment conducted in the DTNSRDC high-speed towing tank, Besch considered only the condition of zero strut yaw angle. The model configurations were found to be stable throughout the speed range utilized. Neither flutter (a dynamic instability) nor divergence (a static instability) was observed up to the highest test speed.

Scaling laws on prototype and model flutter speed have been developed by Besch and Liu.47 According to this study, a strut for a ZOO-ton craft with a 1.69-m chord and TAP flutter model configuration with attached propulsion pod would be stable to at least 110 knots. The theoretical calculation based on the methods given in Reference 47 shows that a further improvement in flutter speed can be anticipated if the propulsion pod is located at the junction of strut and foil as shown in Figure 16. Only the hydroelastic properties of mode 3 are given in the figure. The first and second modes are predominantly first strut bending and first strut torsion respectively. The flutter calculation indicated that they are stable. Mode 3 shows strong coupling of first mode strut bending and torsion.

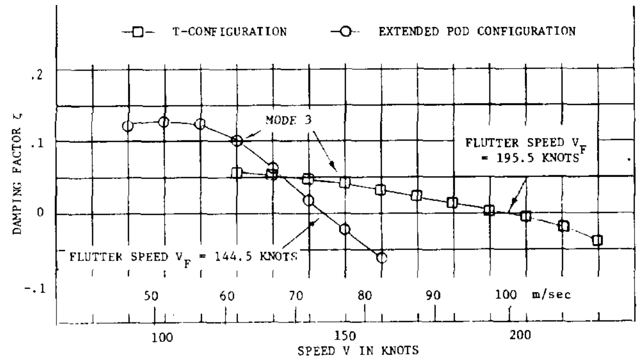

FIGURE 16 - CALCULATED HYDROELASTIC CHARACTERISTICS OF TAP-1 FLUTTER MODEL WITH PROPULSION POD LOCATED IN TWO DIFFERENT LOCATIONS.

A practical high-speed design was produced by specifying a blunt-based strut profile and providing for variable foil cavitation. However, the scaling laws called for the model to be tested at a lower speed than used for a prototype. Only partial cavity on the foil was observed in this study. On the other hand, full cavity on the upper surface of the foil is anticipated on a full-scale supercavitating foil operated at high speeds. Further experimentation should be undertaken to determine strut/foil hydroelastic stability in the presence of a supercavitating foil.

Summary and Recommendations

After a brief review of available literature, foils with supercavitating sections and struts with base--vented sections were selected for high-speed application in this study. Following extensive tradeoff studies between the hydrodynamic efficiency and the structural strength of supercavitating sections, the foil designated as TAP-l was designed for operation at 80 knots (41.4 m/sec.). A base-vented parabolic strut was selected for the TAP-1 foil. Designed by using a conventional approach, this system provided reasonable L/D ratios at high-speed operation. and no leading edge vibration was observed. On the basis of representative hydrodynamic loads (critical loads) established for high-speed strut/foil systems, the feasibility of constructing the TAP-l foil was investigated and verified. However, because takeoff would be difficult with this system, a new strut/foil system (mixed foil and pseudoblunt-based strut) was subsequently introduced and developed as TAP-2.

The structural design for TAP-2 was based on beam theory at 60 knots. Theoretical studies on planoconvex foils *suggest* that a mixed foil at moderate cruising speed can be designed to obtain hydrodynamic efficiency similar to that of existing hydrofoils. A reasonable range of foil-borne operation can thus be anticipated. Takeoff with this new type of strut/foil system should pose no problems. A hydrofoil equipped with mixed foils offers the possibility of reasonably efficient operation at high speeds (above 50 knots) especially in rough seas. This may not be expected of hydrofoils equipped with existing subcavitating airfoils. Strut/foil design methods must be further devoloped to improve efficiency.

Since employment of a mixed foil may require relatively complex control systems, every effort must be made to ease the structural design by minimizing or simplifying the required control devices.

The inability to achieve full natural ventilation on the foil cavity at high speeds has long been considered critical to the development of high-speed hydrofoils. A pseudoblunt-based strut and a parabolic strut with spray wedges were found to be effective in providing full natural ventilation on the foil cavity at high speeds. These results are important for cavity stability control on a supercavitating foil. Additional effort is required to minimize the additional drag associated with the strut spray wedges. Limited experiments on two supercavitating foils in waves indicated that once the superventilated condition was generated, the ventilated flow eondition on the foil was quite stable.

A set of data has been generated on side force and ventilation characteristics of parabolic struts and a pseudoblunt-based strut. Reasonable. maneuvering characteristics of a high-speed hydrofoil were observed in a computer simulation study. The conceptual craft was fitted with supercavitating foils and blunt-based struts. A practical, buildable strut of the TAP strut/pod/foil configuration has been developed. This strut was shown to be stable with respect to flutter and divergence at speeds up to at least 110 knots.

Because of the fiscal limitations, some areas have been investigated only briefly: control devices to reduce lift, the flow boundaries of foil rewetting in waves, the effect of round noses on supercavitating flow performance, a leading edge design criterion in terms of flutter, and smooth transition from subcavitating to supercavitating flow. Efforts in these areas should be continued in order to improve future foil designs.

Acknowledgments

The work reported here represents the combined efforts of many people, some of whom are cited in the references. Their dedication in carrying out specific tasks in support of the total project is acknowledged with appreciation.

Special thanks are also due to Dr. W. Morgan and to Messrs D. Cieslowski and G. Dobay for their helpful discussions and suggestions during the course of this work and to Miss C. E. Wright for administrative assistance throughout the project.

This project was established by the Naval Material Command under Program Element 62754N, Task Area ZF 43 421 001. The preparation of this paper was supported by Element 62543, Subproject SF 43 421 202.

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