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SUPERCAVITATING PROPELLERS
HISTORY, OPERATING CHARACTERISTICS, MECHANISM OF OPERATION

By

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ABSTRACT

This paper contains discussions of: The historical development of supercavitating and ventilated propellers; their operating characteristics; and the mechanism of their operation. A good deal of the material referring to the latter two subjects is presented here for the first time.

The part on historical development includes a discussion, for the first time in recent Western literature on the subject, of the pioneering research of the Soviet scientist V.L. Posdunine and his colleagues.

The operating characteristics are discussed largely in terms of four regimes of propeller operation for which definitions are given. These are: subcavitating, partially cavitating, supercavitating, and fully-supercavitating. The presentation of propeller characteristics in various forms and their meaning is discussed. The arched shape of the fully-supercavitating characteristic curve (k_t vs. J) is described and explained.

New phenomena which dominate the mechanism of operation of supercavitating propellers are described. These are cavity blockage and blade-cavity interference. Some quantitative theoretical results relating to these phenomena are presented. It is explained how these phenomena account for effects on thrust and efficiency, observed experimentally, but not previously understood. Fundamental differences in the mechanism of operation of sub and supercavitating propellers are revealed.

INTRODUCTION

Ten years have passed since the systematic development and exploitation of supercavitating and ventilated propellers was begun in this country. Our progress has been slow but steady. Our present knowledge of the whys and wherefores of these propellers is not by any means detailed enough, but we have sufficient acquaintance with them to be encouraged to design them for installation on large high speed hydrofoil ships and planing craft. In fact, such applications seem likely to grow, since no reasonable alternative for ship propulsion in the speed range between 40 and 80 knots has yet presented itself to us. This is a very important reason why we must continue to work hard on supercavitating propeller problems.

We have had to face a number of very sobering facts since our first experimentation in this country with supercavitating propellers. We early became aware of the terrible strength problems which accompany very high speed propeller operation in seawater. These problems are much aggravated by the thin leading edges with which we would like to equip supercavitating propellers, and they are brought to a virtual crisis by the deterioration of fatigue strength properties in most high yield materials due to seawater corrosion. We have been learning through experience how to live with these problems and to accept the penalties in performance caused by them.

We have also discovered that the thrusting action of heavily supercavitating propellers is unexpectedly poor during off-design operation. For this reason, the provision of adequate thrust to a hydrofoil boat at take-off has become an important element in supercavitating propeller selection and design.

Further, despite our initial successes, we have finally been forced to admit that our only published design methods allow us to predict the thrust or efficiency of supercavitating propellers only roughly, and finally, we have realized that hydrodynamic effects occur during the operation of supercavitating propellers which we had not in the beginning expected or predicted, and we have therefore had to reconstruct the theory of their operation. This has been done to a certain extent, although many details remain to be provided. Nor will this task be easily finished.

I suppose that these experiences are not at all untypical of those associated with new developments of this kind. Typically, too, we somewhat exaggerated the "newness" of the subject. The history of supercavitating propellers does not begin in the 1950's, nor even in the 40's at the time of intensive Soviet studies — but probably in 1894 with the trials of the British steam vessel TURBINIA. It is a very interesting history.

In the present paper I will first try to tell something about the historical development of supercavitating propellers and especially of the pioneering research of the Soviet scientist Posdunine, then to discuss in general terms the important operating features of supercavitating and ventilated propellers and some aspects of their design, and finally to describe briefly those "new" hydrodynamic phenomena which we have recently discovered to be associated with their behaviour. By the latter I refer particularly to the phenomena of blade cascade interference and cavity blockage. The reader must obviously look elsewhere for a discussion of systematic experimental data or for a bold and clear cut formulation of the design process,* but it is hoped that this paper will help him in the interpretation of data or in carrying out an actual design by providing some familiarity with the fairly complicated operating characteristics and mechanism of operation of supercavitating propellers. Much of this material is being presented here for the first time.

HISTORY

Parsons and the TURBINIA

The affair of the British steam vessel TURBINIA provides a very important chapter in the history of ship development. This vessel displaced 44½ tons and was 100 ft. in length and 9 ft. in beam. She was designed and built in 1894 under the sponsorship of a syndicate formed to test the application of the compound steam turbine to marine propulsion. The sponsors hoped that an "unprecedented" speed would be obtained, i.e., a speed somewhat in excess of 30 knots. A single turbine and propeller were initially installed without gear reduction. The turbine was designed

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* In Reference 1 the reader will find the most complete available attempt along these lines.

to develop upwards of 1500 horsepower at a speed of 2500 RPM. The first trials were terrible failures, speeds of only about 20 knots being obtained. In Sir Charles Parsons own words, Reference 2, "Trials were made with screws of various patterns, but the results were unsatisfactory, and it was apparent that a great loss of power was taking place in the screw."

Almost nothing was known about the effects of cavitation on screws prior to the design of the TURBINIA, although at just about that time the trials of the British warship DARING drew attention to the subject, and caused research to be done by S. W. Barnaby and J. I. Thornycroft, Reference 3. This research, together with that conducted subsequently by Parsons, revealed that heavy cavitation was undoubtedly occurring on the TURBINIA's screws and it was thus concluded that this heavy cavitation was the cause of the "great loss of power."

Parson's account of the TURBINIA affair, Reference 2, is decidedly unemotional in style, but it is not difficult to imagine the effect of the first TURBINIA trials on both designer and sponsors, for the failure, which was due to completely unanticipated effects, clearly threatened to jeopardize their entire venture and investment. In fact, the severity of the difficulties drove the designers finally to a rather extreme but successful solution involving the replacement of the single turbine by three smaller turbines of equivalent total horsepower; these drove, without reduction, nine screws arranged three in tandem on each of three arallel shafts. In 1897 several sets of screws of different pitch were tried and the refitted TURBINIA finally achieved a speed of

32.60 knots, bringing success to the venture and what must have been immeasureable relief to the designers and sponsors. Parsons and his colleagues subsequently crowned this achievement with further technical and business success in the development, adaptation, and manufacture of steam turbines for marine use. Of course, the eventual success of the steam turbine depended very much on the introduction by Parsons of reduction gears — thus really saving the "cavitation crisis."

Parsons experimental studies in the two years following the initial trial failures were made on 2-inch screw models operating in a circular tank of almost boiling water and observed with a stroboscope (of his own design!). In this way he was able to observe not only the onset of cavitation but even supercavitating operation. He described some of his observations as follows: "It appeared that a cavity or blister first formed a little behind the leading edge and near the tip of a blade; then, as the speed of revolution was increased, it enlarged in all directions, until, at a speed corresponding to that in TURBINIA's propeller, it had grown so as to cover a sector of the screw-disc of 90 degrees. When the speed was still further increased, the screw as a whole revolved in a cylindrical cavity, from one end of which the blades scraped off layers of solid water, delivering them on to the other. In this extreme case nearly the whole energy of the screw was expended in maintaining this vacuous space. It also appeared, when the cavity had grown to be a little larger than the width of the blade, that the leading edge acted like a wedge, the forward side of the edge giving negative thrust."

The exact connection between such observations and the operation of the TURBINIA's screw remains unclear, both because the experiments were carried out in water whose speed was undetermined, and because the scaling procedure utilized is rather vague. Nevertheless, the first failures of the TURBINIA and these experiments together made evident in dramatic fashion the horrors that can attend the operation of heavily cavitating propellers. The experience of others in Britain at about the same time taught of the ills to be visited in the form of blade erosion by permitting even relatively small amounts of cavitation to exist on a screw. These lessons were perhaps too well learned; the horrors thus revealed seem in fact to have been sufficiently blinding so that for the following forty years man felt hardly compelled, even out of scientific curiousity, to study in a rational and systematic way the operation of heavily cavitating screw propellers. Thus our scientific understanding remains relatively underdeveloped even at the present time.

The practical possibilities for high speed propulsion utilizing supercavitating operation were of course not completely neglected during this period, and without the aid of any theory or rational design methods, heavily cavitating screw propellers were and still are successfully used to propel small racing boats at speeds well in excess of 100 knots. A great deal of trial and error in propeller choice must be involved in such applications since the attainment of proper rotative speed is crucial for the optimum performance of racing engines.

Early Soviet Work — V. L. Posdunine

In about 1940, V. L. Posdunine, a Soviet scientist and member of the Academy of Sciences of the USSR, seems to have commenced his systematic studies of heavily cavitating screw propellers, References 4-11; he also inspired other Soviet work, References 12-15. Posdunine's studies are remarkable in a number of respects. In the first place, they comprise, as far as I know, the first really rational and systematic studies of the subject, although other individuals had certainly tested and observed, in isolated instances, propellers operating under heavily cavitating conditions. Posdunine's work was especially strong on the experimental and intuitive side (the theory being weaker) and he observed and discussed phenomena which have only recently received notice and attention in our own work. For instance, he was well aware that the inflow to a supercavitating propeller is quite different than that to be expected from the theory of subcavitating propellers or from actuator disc theory; in fact, he wrote of observing during water tunnel tests that the inflow speed at a heavily supercavitating screw was actually <u>less</u> than the approach speed far ahead of the screw; for this reason he undoubtedly inspired a series of Soviet theoretical studies, References 12-14, attempting (unsuccessfully) to derive an appropriate momentum theory for supercavitating propellers. He also seemed to understand the importance of blade interference for the operation of supercavitating propellers; he had conducted (others actually performed the tests) experiments on a systematic series of screws with blade numbers from 2 to 16 and blade area ratios from .09 to

1.12; he also stimulated theoretical work on non-linear cascades of flapped supercavitating profiles, Reference 15. Posdunine was in fact so impressed by the new effects introduced into propeller operation in the supercavitating regime that he wrote "The operational differences between supercavitating and ordinary non-cavitating propellers are so great in point of physical phenomena that no common theory of operation or single type of construction will suit the two kinds of screw." He clearly recognized the importance of blade profile shape and by 1945 had carried out experiments on at least 28 hydrofoils in a wide variety of shapes; the most advanced of these look like good shapes to us except that they are much thicker than we would ordinarily use, see Figure 1. He failed, probably for this reason, to produce lift-drag ratios greater than 8.5. Posdunine did, however, determine from his experiments at least two very fundamental facts about supercavitating profiles: (i) that their quality decreases with increasing thickness, and (ii) that for best results they should be operated at an incidence close to that for "shock-free entry." Much of his systematic experimentation, particularly on screws themselves, has not yet been paralleled by us and, unfortunately, he described his results in only general terms.

In his published work (1941-47) on supercavitating propellers, Posdunine made a plea for a better theoretical understanding of the various important aspects of supercavitating propeller flow, including: supercavitating flow about profiles and the inflow to a supercavitating propeller. The published Soviet work in emphasizing fundamentals, seems to fail in presenting useful formulae or methods which allow for the design of a cavitating screw or for the prediction of its performance, and we are left only to wonder whether supercavitating propellers of rational design have found application in the USSR. Posdunine's insight into the problems of supercavitating propellers seem most impressive, despite the fact that his insights found, at best, weak expression in analytical terms. While foreseeing most of the problems, he did, however, seem to neglect in his published work the structural problems that must be dealt with in supercavitating propeller development — or can this perhaps be the reason that he experimented, finally, with such thick hydrofoil sections?

The existence of Posdunine's work was vaguely known in the West, but except for an early article in English, published in the Transactions of the Institution of Naval Architects - Reference 5, it was not read. Posdunine's views and his simple theory as expressed in his short British paper of 1943 are difficult to understand - the theory is in fact incorrect in its assumptions — and this is probably the reason why he did not inspire us. He did of course succeed in introducing the word "supercavitating" into the English language, through the publication of Reference 5. From Great Britain this word seems to have been imported directly into the David Taylor Model Basin.*

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* In view of this fact is does seem a little ironical that a great literature having been built up here on the subject of <u>supercavitation</u> and <u>supercavitating</u> propellers, a movement has been inaugurated recently in Great Britain to introduce instead the use of the term "heavily-cavitating."

Developments at the David Taylor Model Basin

Without any knowledge of the history so far recited, I began theoretical studies of supercavitating two-dimensional flows at the David Taylor Model Basin in about 1952. These were at first definitely not inspired by a specific interest in propellers or hydrofoil craft, but by a simple curiousity about the form of theory for thin bodies in cavity flow. For my beginning knowledge and interest in cavity flows, I was entirely indebted to References 16 and 17 and to conversations with Phillip Eisenberg. The first application of linearized theory to supercavitating flow was for the case of thin strut shapes, Reference 18, and then with a growing interest in practical applications (as anticipated in the Introduction to Reference 20) for the case of lifting hydrofoil sections, References 19-21. Thus the principal of design for low drag was discovered and applied, as an example, to the design of a particular hydrofoil section.

These theoretical results suggested, somewhat optimistically, "that supercavitating hydrofoil sections could be designed with efficiencies comparable to those of fully wetted sections." Thereupon the utilization of a theoretical low drag section in a supercavitating propeller was undertaken in early 1954, at first by H. Lerbs and later by A. Tachmindji.* As part of this effort, the calculation of upper cavity streamlines was undertaken in 1954

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* A number of other people at the Taylor Model Basin played an important role in this early development, including: Mr. William Morgan and Cdr. (now Capt.) Patrick Leehey, U.S.N.

by the author and Miss Phyllis Burkardt, but was unfortunately not included in any unclassified work. It was first attempted to design a three-bladed propeller, but this was too highly stressed because of the thin blade sections being utilized, and a two-bladed design was finally accomplished, TMB Propeller 3460. It was lightly loaded (C_T = 0.145); of low blade area ratio (BAR = .196), and of moderate pitch (Pitch Ratio = 1.107). It is further described together with its performance and the design method utilized in Reference 23. This initial supercavitating propeller, designed according to theory and without the use of any experimental hydrofoil data whatsoever, was exceedingly successful in that the design performance with regard to thrust and efficiency were very closely verified during tests. The design method utilized may be described as imbedding two-dimensional supercavitating theory (linearized) for the profile performance into conventional (Reference 22) modern blade element theory. Thus no account at all is taken of possible interference (blade cascade) effects on the blade elements, of possible blockage effects that the thick cavity body might have on the approaching flow, or of the possible effect of the cavities on curvature or pitch corrections. Indeed, the experimental results in verifying the design performance suggested that such effects could be safely ignored, and such was the interpretation universally given them. This interpretation was strengthened by the similar success of a second supercavitating propeller of somewhat different characteristics (TMB Propeller No. 3509, Reference 23; C_T = 0.28; 3 blades; BAR = .332; Pitch Ratio = 1.533), which was in addition to laboratory tests installed on a small hydrofoil craft. Problems of propeller strength were to a certain extent recognized and dealt with during these early developments and a practical design method incorporating hydrodynamic (as previously indicated) and structural considerations resulted, References 23 and 24. However, the structural design remained based on the criteria of spanwise bending stresses (Taylor's method), ignoring chordwise bending. The latter turn out to be important for high speed propellers with thin leading edges. This design method thus ignores both important hydrodynamic and structural effects. It nevertheless has served valiantly, succeeding very well in its early applications and it remains the only design method for supercavitating propellers yet set forth in print; designers are therefore much indebted to the Taylor Model Basin and the authors of this method.

These initial developments at the Taylor Model Basin have been steadily expanded there, mainly through further propeller testing in both tunnels, towing tanks, and on small boats, References 25-34 ; these are well reviewed in Reference 1. These tests have resulted in a better understanding of what may be expected in the way of operational characteristics of supercavitating propellers, if not in an increased understanding of their mechanism of operation. Outstanding, in our opinion, among the revelations of these tests were the discoveries: (a) that the thrust coefficient for a fully supercavitating propeller possesses a maximum, (b) that strength problems including leading edge vibration or "flutter" are of great importance in actual applications of supercavitating propellers and (c) finally, that the conventional method of analysis of supercavitating propellers often does not lead to accurate predictions of thrust or efficiency. The Taylor Model Basin also introduced the ventilated propeller, which operates with artificial cavities created by the introduction of air to the suction side of the blades, References 25 and 28. This work was then followed here very closely by intensive studies of ventilated propellers at the Naval Ordnance Test Station (NOTS) in Pasadena, California.

Ventilation

It had been known at least since the wartime work of Reichardt in his water tunnel at Göttingen, Reference 35 , that air may be used to create cavities behind blunt bodies and thereby produce flows which may be quite precisely correlated with natural cavitating flows on the basis of equal cavitation number, defined as the ratio of the difference between ambient and cavity pressure to the dynamic head. Some of Reichardt's experiments were repeated at the Taylor Model Basin just after the war by Phillip Eisenberg and Hartley Pond. Attention was drawn not only in this way to so-called ventilated flows, but during the same period a good deal of experimental and theoretical interest in cavity flows had been stimulated by problems involving the air-filled cavities formed during the water entry of air launched torpedoes. We were therefore quite consciously aware of the possibility of ventilated flows from the beginning of our research.

In 1955 just after the publication of Reference 20 and apparently in response to the predictions of the theory contained therein, personnel of the Hydrodynamics Division of the Langley Laboratory of the then National Advisory Committee for Aeronautics (NACA) began both experimental and theoretical studies of supercavitating flows. The greatest part of this work was done by Virgil E. Johnson, Jr. The aim of Johnson and his co-workers was to provide information which might lead to improved take-off and alighting gear for water-based aircraft. They saw in supercavitating operation a possible way to avoid the dangerous transition from fully wetted to cavitating flows which had up to that time prevented the use of hydrofoils at high speeds. In the beginning of this work it was realized that ventilated rather than naturally cavitating operation offered the better prospect for smooth operation from relatively low speeds to take-off. The NACA work did indeed confirm the advantages and reveal the feasibility of ventilated wing systems, Reference 36 . In fact, at the very early initiative of Eugene Handler of the Bureau of Naval Weapons a ventilated hydrofoil was designed and has been successfully applied to a small water-based aircraft, Reference 37 . Further, in good part as a derivative of the early NACA work, very intensive studies of ventilated wing systems for high speed hydrofoil craft are being carried out today in various laboratories, including our own.

Thus was the stage well set for the introduction of the ventilated propeller in 1959. Taylor Model Basin tests, including air requirement measurements, on a simple propeller operating both ventilated and with natural cavitation showed, as was to be expected, that performance was the same in the two modes of operation, the cavitation number being fixed, Reference 25. More recent Soviet tests have shown the same thing, Reference 38. The Soviets have gone on to utilize ventilation in order to operate supercavitating propellers on self-propelled models at Froude scaled speeds. In this way and by pressure measurements on the model stern they have shown that supercavitating propellers may be expected to reduce thrust deduction. Theory leads to the same conclusion, as we shall see in a later section of this paper.

The Naval Ordnance Test Station (NOTS) in Pasadena, California, together with the Ordnance Research Laboratory at Penn. State University, has during the last four or five years conducted intensive studies of ventilated propellers of both the supercavitating and base ventilated type. They have published very interesting accounts of their research, References 39 - 42, which included tests both in a water tunnel and on a 10 ft. torpedo-like body run on a cableway. The effect of air flow rate to the propellers on the thrust, efficiency and radiated noise were determined. This research was of a pioneering nature in many regards. Almost in their own words, "a number of important advances...(were) made for the first time: (a) a ventilated propeller was used to propel a marine vehicle, (b) a gas other than air was used for propeller ventilation, and (c) a supercavitating propeller was used to propel a torpedo-like vehicle." Although the final consequences of the NOTS tests are unclear, they certainly demonstrated the general feasibility of ventilated propellers for real applications. In connection with the NOTS experimental studies of ventilated propellers, particularly of the base-vented type, it should be mentioned that these were unquestionably very much stimulated by certain theoretical and experimental work on base-vented hydrofoil sections conducted in the same laboratory, References 43 and 44; this work closely parallels that of Johnson, Reference 45, and has been followed by more recent studies, Reference 46.

Ventilation clearly offers the possibility of operating supercavitating propellers at lower forward speeds than would otherwise be possible — even, as the Soviets showed, at the very low speeds associated with towing tests. This is certainly an enticing possibility, but no full scale applications to ships of any size have, to the best of my knowledge, been made. The development of ventilated propellers is continuing, though, as for instance through studies of air requirements, ventilation inception, and cavity pulsations, References 47-50.

It is worth noting, incidentally, that almost all steady cavity flow theory is equally applicable to ventilated and natural supercavitating flows since no account is taken of the exact nature of the light gas within the cavity. This is not, however, true of unsteady cavity flow theory where the compressibility of the cavity gas is crucial and must be taken into account.

Developments Abroad

Following the publication of the early Taylor Model Basin work and the 2nd ONR Symposium on Naval Hydrodynamics, active interest in supercavitating propellers spread abroad, particularly in Sweden, Great Britain, the Netherlands and Japan. Activity has involved actual application to high speed planing boats (about which no detailed reports on performance or operating experience are yet available) and tunnel testing. These foreign tests contribute well over half of the more than 30 separate supercavitating propeller test results available today, References 51-54. In addition, some foreign tests have not been reported, as in the case of a series of 12 propellers which have been tested by KaMeWa of Sweden. Incidentally, all of the test results available refer to propellers tested according to the DTMB design method, Reference 24, with the exception of the so-called Newton-Rader series, Reference 51. These latter propellers utilize blade sections developed empirically and quite unlike our own sections, Figure 1.

Variable pitch supercavitating propellers were quite early suggested and tested by KaMeWa of Sweden, and the latter has made available some test results which show what might be gained during off-design operation by a variable pitch installation, Reference 54.

These are confirmed by some tests conducted in our own water tunnel for the Hamilton Standard Division of the United Aircraft Corporation, Reference 55, which I shall touch upon again later.

Among the more interesting tests conducted abroad were those at the NSMB in Wageningen, Reference 52, in which supercavitating screws of different sizes were tested in a solid wall tunnel in order to obtain information on wall effects. These revealed the existence of no such effects, and this may be explained theoretically, as we mention again later in discussing the momentum theory of supercavitating propellers. Also in connection with wall effects, certain propeller tests carried out for HYDRONAUTICS in a solid wall tunnel at the Swedish State Experimental Towing Tank in Gotëborg are interesting. In these tests we specified that the length of the cavity behind the propeller be measured. In fact, over part of the measurement range, which included very low advance coefficients, the cavity extended completely down the tunnel — thus causing choking. This phenomena may also be explained and predicted theoretically with the aid of momentum theory.

Other Developments Here

We have already referred herein to the work at the Taylor Model Basin and to ventilated propeller tests at the Naval Ordnance Test Station in Pasadena. Besides these, other very important work related to the theory and application of supercavitating propellers has been conducted elsewhere in the United States during the last nine or ten years.

Motivated by the promise held forth by the predictions of the earliest theory, References 19 and 20, and by the possibility of supercavitating applications to hydrofoil boats and propellers, the Mechanics Branch of the Office of Naval Research deliberately undertook to support, encourage, and co-ordinate a research program in the area of supercavitating flows starting in late 1955.

A number of groups in Universities were supported under this program, including those in the Hydrodynamics Laboratory at the California Institute of Technology, the St. Anthony Falls Laboratory of the University of Minnesota, the Mathematics Departments at the Renssalaer Polytechnic Institute and at the Delft Technical University (the Netherlands), and the Ordnance Research Laboratory at the Pennsylvania State University. In addition the ONR undertook to provide the means for technical co-ordination of the Navy's in-house interests in this field, particularly between certain interested groups in the Bureau of Ships, the Bureau of Naval Weapons and their laboratories. The ONR further sought to encourage scientific interest in supercavitating flows through the 2nd ONR Symposium on Naval Hydrodynamics in 1958, one-half of which was devoted to that subject. In fact the collected papers of that Symposium already reflect the success of the ONR, even at that early date, in stimulating activity in this field of research. Much of this work, which was both theoretical and experimental, served to elucidate our understanding of supercavitating flow past foils and wings, of wall interference, of cascade flows, and of unsteady effects. It has provided an invaluable foundation for the research and applications which followed, both in reference to propellers and hydrofoil wings.

During the past five years the groups most active in theoretical research on supercavitating flows have been located at the California Institute of Technology, NOTS Pasadena, Stanford University, and at HYDRONAUTICS, Incorporated. A thorough review of the literature is not available, but reasonably lengthy bibliographies are available (in the form of references) in References 56 and 57 ; these are supplemented by certain references in the present paper.

The intensive HYDRONAUTICS effort in the field of supercavitating flows has been very closely associated with propeller development. This work has been supported primarily by the Bureau of Ships of the U. S. Navy. It has involved theoretical and experimental research and full scale design. Some of the results of our theoretical research on the mechanism of operation of supercavitating propellers are indicated in another section of this paper; these results largely explain the off-design operation of supercavitating propellers and have led to improvements in design. In addition to this work, detailed studies of the performance of a wide variety of hydrofoil sections, including strength as a parameter, have been carried out, References 58 and 59 . Without results such as these it is not possible properly to design supercavitating propellers taking strength into account. We have also introduced two new features in section design, which improve very much the strength qualities of useful sections. These are: (a) the section annex, which is appended to the base of the usual section within the cavity envelope, thus increasing its bending strength without interfering with its hydrodynamic operation while supercavitating and (b) the use of almost parabolic thickness in addition to camber and incidence, thus increasing in an optimum way both the strength of the nose in chordwise bending and the spanwise bending strength of supercavitating sections. A section utilizing both of these features is shown at the bottom of Figure 1.

In early 1960, HYDRONAUTICS undertook studies of propellers, pod and tail strut for the H. S. DENNISON, a 100 ton, 60 knot hydrofoil ship built by the Grumman Aircraft Corporation for the U. S. Maritime Administration. It was recognized from the beginning that the propellers would have to be supercavitating. After a study of alternatives, including dual propellers mounted fore and aft on a nacelle, it was decided to utilize a single propeller mounted at the aft end of a fully wetted pod and attached to the hull by a vertical strut of very special design. It was during the first tests (at the DTMB) of a three bladed propeller of our design for the DENNISON that it was first discovered that a supercavitating propeller suffers adverse loss of thrust at low advance coefficients; previous available supercavitating propeller tests had not been conducted at sufficiently low advance coefficients to reveal the arched shape of the fully supercavitating thrust characteristic curve. It was this discovery that sparked our studies of cavity blockage and blade interference effects, which are discussed later in this paper. This first propeller proved unsuitable for a number of reasons and we subsequently designed and had manufactured in stainless steel a two-bladed 42 inch propeller of pitch ratio 0.98 employing low-drag annexed sections and a blade area ratio of 0.25. Many of the design features incorporated were a result of concern about the provision of adequate thrust at take-off, as this became of great importance to us following the revelations of the earlier tests. This two-bladed propeller was tested, final revisions in design incorporated, manufactured, and finally utilized to power the DENNISON during her very first trials in July 1962. Quite adequate hydrodynamic performance both off-design and at the cruise speed were attained, the propeller being very well matched to the turbine, Reference 60, as is essential for fuel economy and best turbine utilization. After a few hours of operation this propeller failed in an outboard region near the leading edge probably due to corrosion fatigue. This failure had been preceded about a week earlier by the very similar failure of a quite different three-bladed supercavitating propeller of Taylor Model Basin design during high speed model tests. These failures together led to the realization that chordwise bending could not be neglected in the design of supercavitating propellers and that available methods of propeller stress analysis are therefore quite inadequate. An alternate three-bladed propeller of Taylor Model Basin design was already under construction prior to and during the first trials of the DENNISON and following the failure of our two-bladed propeller, this alternate screw was modified to thicken the leading edges and was subsequently utilized, Reference 60.

The DENNISON was a successful and very useful pioneer in many respects. Speaking only of the propeller, she demonstrated that a supercavitating screw could successfully take-off and propel a large hydrofoil boat at speeds even in excess of 60 knots with propeller efficiencies in the neighborhood of 60 percent and while absorbing powers approaching 15,000 h.p. Furthermore it was demonstrated that this would be done while obtaining a good matching between the propeller and turbine. This achievement involved a solution to the problem of mating the propeller, pod and supporting strut, and of the recognition and partial solution of the off-design problem for supercavitating propellers. Finally, of course, the experience with the DENNISON taught us the invaluable lesson that stress problems for high speed propellers operating in seawater are more severe even than we had thought.

The design and construction of the DENNISON was overall a bold project. In connection with propulsion it must be particularly pointed out that the successful development of shafting, gears, and turbine by the General Electric Company, to deliver over 15,000 h.p. from the hull to the submerged screw through a long right-angle drive system was a noteworthy engineering achievement.

The use of naturally supercavitating propellers is limited to sufficiently high forward speeds and loadings; therefore difficulties arise in many potentially fruitful applications involving speeds where the operation of subcavitating propellers is inevitably accompanied by serious harmful cavitation, but which are yet not high enough for naturally supercavitating propellers, Reference 61. The ventilated propeller offers the possibility of supercavitating operation at quite low forward speeds, as we have commented here already. So, too, does the naturally supercavitating propeller in a Kort nozzle which we have proposed and studied analytically, Reference 62 . This system seems to offer particular advantages for the propulsion of hydrofoil craft in the speed range between about 20-40 knots and would therefore seem to deserve some experimental study.

In order to bring this history right up to date, a recent interesting development might be mentioned. It involves the proposal for a variable camber supercavitating propeller by George Rosen of the Hamilton Standard Division of the United Aircraft Corporation. The propeller would employ a hinged forward portion. We have recently designed and tested such a supercavitating propeller for the United Aircraft Corporation, Reference 55; these tests indicate that a marked improvement in off-design thrust capability is attainable with a variable camber propeller in comparison both with fixed pitch and variable pitch propellers. These results are not only of potential practical importance, but they seem to us to confirm our theoretical conclusions (as discussed later in this paper) regarding the nature of the off-design problem and the importance of camber in dealing with it.

GENERAL CHARACTERISTICS OF CAVITATING PROPELLERS

Definition of Supercavitating Operation

The onset of cavitation on a marine propeller has been described many times. Cavitation may occur first in the hub vortex, the tip vortices, or on the blades. At first appearance it has little effect on the propeller performance, although it may be accompanied by blade erosion and radiated noise. The appearance and extent of cavitation depends both upon the cavitation number based on rotative speed, σ_n, and the propeller loading. In general the spread of cavitation over a blade is accelerated by reducing σ_n and increasing the propeller loading. Cavitation generally spreads from the tip downward to the hub. This is illustrated in Figure 2, showing the cavitation patterns and thrust associated with propeller operation over a range of rotative speeds, the forward speed and ambient pressure being fixed. The spread of cavitation is seen to be accompanied by a diminishing of the rate at which thrust increases with rotative speed, until when cavitation occurs over nearly the whole blade, an increase of RPM may (as in the case illustrated) result in no additional thrust, or even a slight decrease of the latter. In these cases the losses due to cavitation completely absorb the additional power supplied to the screw. If, however, the rotative speed is even further increased, then the thrust generally rises again. This is illustrated in Figure 3 which is schematic based on actual test data. At the same time the cavities become longer and more fully developed. It is at this stage that the propeller may be said to be supercavitating. To be precise, we may define supercavitating operation as beginning at the rotative speed where the rate of thrust increase with rotative speed is first a minimum, the forward speed and ambient pressure being held fixed. This definition is in part arbitrary, but it is based on the experimental observation that the thrust increases more rapidly with rotative speed once the spread of cavitation over the blade from tip to hub is completed.

In Figure 4a are presented the thrust characteristics of a supercavitating propeller obtained in towing tank tests with simulated cavitation (ventilation), Reference 38. They represent the most complete set of thrust characteristics for a single propeller known to the author and they are at the same time typical of other available data. The propeller was 3 bladed, had a pitch-diameter ratio of 1.4, an area ratio of 0.51, and utilized "wedge sections which are usual for supercavitating propellers" although "due to the necessity of setting the tubes for air supply and cavity pressure measuring, the blade thickness including the thickness of the leading edge was increased in comparison with the predicted values." The operating characteristics for the same propeller are shown in somewhat different form, Figure 4b, where contours are given for constant values of σ_n rather than σ_o (note that the cavitation number based on true tip circumferential speed would be about $\sigma_n/10$). These curves are very instructive. They do not, however, permit the rapid determination of conditions which correspond to supercavitating operation. For this purpose, these same thrust characteristics are presented in a different form in Figure 5; here the slope of a given contour is proportional to the rate of change of thrust with rotative speed (forward speed and ambient pressure fixed). Utilizing the definition of supercavitating operation just given, the region so defined is drawn in and is later used in constructing Figure 6. The narrow extent of this region is quite evident, and particularly striking is the shrinking of this region down to the so-called fully supercavitating line for low advance coefficients. This diagr also reveals that for low J's there exists a rotative speed for which the thrust is a maximum, the forward speed and ambient pressure being fixed.

The chart shown as Figure 5 (C_T vs. $1/J$; σ_o fixed) seems very useful to us and we recommend it for propulsion system analysis. For instance, the thrust required vs. forward speed for a given craft may be plotted on the same diagram, the propeller diameter having been tentatively selected, and the required rotative speeds and regimes of operation of the supercavitating propeller are then exhibited in a particularly clear way for the whole speed range of the craft.

Fully Supercavitating Operation

Imagine that the rotative speed of a propeller has been increased until supercavitating operation begins, and is now fixed along with the forward speed, but that the ambient pressure is decreased or, equivalently, that the cavity pressure is increased. The thrust acting on the propeller will now at first decrease, because the lifting effectiveness of the blade elements is reduced by the effective increase in pressure on the suction side (reduction in blade cavitation number). As the blade cavitation numbers based on true rotative speed approach zero (say - become less than .03 or so) further loss of effectiveness with reduction of ambient pressure is virtually halted. The thrust thus approaches a certain limiting value which depends on the advance coefficient and is hardly affected by further decrease of the cavitation number. We might then say that the propeller is fully supercavitating. The typical characteristic curve for fully supercavitating operation may be roughly described as a circular or parabolic arc with a maximum near the middle of the propeller's J range. This curve is quite apparent in Figures 4a and 4b.

Fully supercavitating operation of propellers is of great importance for high speed hydrofoil boats (say 50 knots and up), both at cruise and take-off conditions. For example, take a boat with a cruise speed of about 50 knots ($\sigma_o = 0.4$), a take-off speed of about 23 knots ($\sigma_o = 1.9$), using the supercavitating propeller whose characteristics we have been discussing. Suppose this propeller has been designed for $k_t = 0.065$ and $J = 0.76$ at the cruise point. Further suppose that the take-off at 23 knots requires the same thrust as at cruise. Then take-off ($\sigma_o = 1.9$) will occur close to the point on the fully-supercavitating curve at $J = 0.4$ and $k_t = 0.065$. The figures used are typical for a hydrofoil craft, and they demonstrate that high speed hydrofoil boat propellers are likely to be fully supercavitating or nearly so, at both the cruise and take-off points.

Note that the cruise condition is to the right and the take-off condition to the left of the maximum in the fully-supercavitating characteristic curve. In testing a propeller for application to a high speed hydrofoil boat it is therefore important to obtain data adequate to define this curve over a reasonable range about its maximum. In fact, the first evidence that this curve possessed a maximum at all was obtained in tests at the Taylor Model Basin of a 3-bladed supercavitating propeller designed for the H. S. DENNISON. The shape of this curve is, of course, unfortunate in that for the lower advance coefficients it implies reduced thrusting ability of the propeller with reduced forward speed. The propeller efficiency is at the same time dropping with decreasing advance coefficient. The attainment of adequate thrust at take-off, where more is generally needed than at cruise, is thus made difficult both because of the danger of running out of turbine RPM and of turbine torque (or power). Fortunately, properly designed supercavitating propellers generally manage at take-off if the thrust required there is not too much more than the thrust required at cruise.

The shape of the fully supercavitating characteristic curve is at first glance startling and unexpected, for the reason that it implies for operation to the right of the maximum in the curve a loss of lifting ability on the blades (reduced k_t) accompanying an increase in the relative flow angle to the blades (reduced J). In fact, we are now quite convinced that this actually occurs, and that the explanation lies in the interference between a blade and the cavity shed from the preceding blade. This interference tends to reduce the blade lift by an amount which increases as the spacing between blade and preceding cavity narrows - as occurs when the advance coefficient is reduced. Over all of the fully-supercavitating operating range this blade-cavity (or cascade, as we sometimes call it) interference is important and it dominates the flow behavior at the lower advance coefficients. Later on in this paper we shall give some theoretical justification for these statements and we shall describe in a little more detail the nature of the flow through and about fully-supercavitating propellers. Let us only state here that quite different phenomena than we are used to for non-cavitating propellers accompany the operation of fully-supercavitating propellers; that not only is the interference between blades and cavities important, but also the overall blockage to the flow which is due to the great volume of cavities around the blades; and that as a result we must be prepared to construct a new and appropriate theory of the operation of fully-supercavitating propellers.

Partially Cavitating Operation

The particular supercavitating propeller under consideration seems to operate over almost all of its thrust characteristic diagram in a partially cavitating state. By the latter we mean that a cavitation sheet does not completely cover the blade back. Generally speaking, operation in the partially cavitating regime is to be avoided as it may be accompanied by harmful cavitation.

The partially cavitating regime may be divided into two parts, separated by a line of "maximum thrust." To the high J side of this line an increase in rotative speed, the forward speed and ambient pressure being fixed, results in an increase in propeller thrust, while to the low J side of this line the same increase in rotative speed causes a loss in thrust. This latter behaviour is similar to that experienced by a fully supercavitating propeller at suitably low advance coefficients, and is probably due both to the spread of the cavitation pattern down to the inboard portion of the propeller and to the onset of blade-cavity interference. The existence of these regions and the line of maximum thrust are of considerable practical importance, for they reveal that only limited amounts of thrust can be produced by a given propeller for a given σ_o, and that this maximum thrust is not necessarily produced at the highest attainable rotative speed.

The Four Regimes of Propeller Operation

A great deal more might be said about supercavitating propeller operation such as can be deduced from the various thrust characteristic curves of the type presented here, but we must be satisfied for the present to have defined and briefly commented on the various regimes of operation and briefly to discuss the static thrust situation.

The four (or five) regimes of propeller operation discussed so far are depicted in Figure 6. A map such as this is useful in the interpretation of data presented in the usual k_t- J diagram. The definitions of these regimes have been given earlier in this paper and we have also given some idea about how the flow about the propeller is different in these various regions. This information is summarized below:

1. Non-Cavitating - No significant cavitation. Thrusting ability increases sharply with decreasing advance coefficient. Thrust increases at least as rapidly as rotative speed squared. A single thrust characteristic curve.

2. Partially Cavitating - Significant cavitation present, but cavitation patterns are not completely developed. Part of the blades may not be cavitating. A family of thrust characteristic curves which depend upon a cavitation number. Thrusting ability generally decreases sharply with decreasing advance coefficient (for σ_o fixed) or cavitation number (for J fixed). Regime divided into two parts by a line of maximum thrust (for fixed σ_o):

(A) INCREASING THRUST REGIME: On the low J side of the maximum thrust line an increase in rotative speed results in an increase in thrust. Cavitation effect thus relatively weak.

(B) DECLINING THRUST REGIME: On the high J side of the maximum thrust line an increase in rotative speed causes a loss in thrust. Effect of spreading cavitation and blade-cavity interference thus predominate.

3. Supercavitating - Cavitation patterns fully developed. All blade elements operating in supercavitating flow. However, local section cavitation numbers are high enough so that effectiveness of blade elements decreases with decreasing σ_n, causing thrust loss. A compact family of thrust characteristic curves. Interference effects between blade and the cavity from the preceding

blade are important. Cavity volume large and causes important blockage effects on the inflow to the propeller.

4. Fully-Supercavitating - Section cavitation numbers very low (σ_n approximately less than 0.25 - 0.30 for most of the J range), so that effectiveness of blade elements ceases to change significantly with decreasing σ_n. A single thrust characteristic curve of arched shape. Pronounced blade interference and blockage effects. Inflow and blade element performance quite different than for non-cavitating propellers. This regime is of considerable importance for high speed hydrofoil craft and for ship propulsion at speeds in excess of 40 - 45 knots.

Static Thrust

A propeller can suffer severe deterioration of its thrusting ability due to cavitation even at zero forward speed if it is operating at high rotative speeds. In fact, based on the evidence presented in Figure 6 it seems likely that static thrust operation often occurs in the "declining thrust" portion of the partially cavitating regime, and this means that the propeller operation is dominated by the effects of cavitation, including blade-cavity interference. There exists no adequate theory to deal with operation in this regime. It is therefore especially useful to have such thrust data as are presented in Figure 4a for low and zero advance ratio. These data are not presented in that figure in their most useful form for the rapid estimation of static thrust, and in Figure 7 are shown the results of a replotting in the form of 8 $k_t/\pi\sigma_n$ vs. $1/\sigma_n$. The advantage of this curve is that it immediately allows an estimation of the variation of thrust with rotative speed.

Efficiency

A subcavitating marine propeller suffers power losses on account of the friction acting on its blades and on account of the kinetic energy which it transfers to the fluid passing through its disc (induced losses). The former depends on the blade area and to a certain extent on the blade loading, while the latter depends largely on the net thrust loading, C_T; therefore the relative losses due to these two distinct causes depends very much on the net thrust loading. For moderately or lightly loaded subcavitating propellers, the frictional losses will usually predominate.

A supercavitating body generally (although not always) experiences a pressure drag which accompanies the separation of the flow streamlines and which has no counterpart in the smooth flow about a streamlined body such as a subcavitating blade element at normal loadings. The shape of modern supercavitating foils is constructed to minimize this pressure or cavity drag. Nevertheless, the losses suffered by a heavily supercavitating propeller are largely due to cavity drag. Other losses, usually smaller, are also incurred due to the friction drag on the pressure face and in many cases where the cavity thickness is inadequate, by friction on the upper blade surface. The induced losses are, we believe, much less for a supercavitating propeller than for its subcavitating counterpart operating at the same net thrust loading. In fact, ideal efficiencies greater than unity may be experienced by supercavitating propellers. This situation is discussed later on in this paper.

Despite the possible alleviation of frictional and induced losses, the efficiencies of supercavitating propellers are in general not as high as those enjoyed by properly designed subcavitating propellers operating at the same thrust and advance coefficients. Of course, it is often not at all possible to avoid cavitation, because the speed or loading is too high, and in such cases a properly designed supercavitating propeller is called for, not always because of efficiency but often in order to avoid blade erosion. But all of this is well known, References 1, 24, and 61.

The cavity drag of supercavitating blade elements depends very much on the foil shape, References 19-21, and the use of appropriate camber is crucial for the production of optimum blade efficiency. Detailed theoretical studies of two-dimensional supercavitating foil design including strength as a parameter have been carried out, References 58 and 59. It has not generally been appreciated, however, that the two-dimensional efficiency of supercavitating blade elements is degraded in application to a propeller or wing due to the reduction in blade lift effectiveness caused by finite span effects; this is discussed again later in this paper.

Achievable supercavitating efficiencies depend upon a variety of parameters. Foremost among these are: loading (C_T), advance coefficient (J), and strength requirements. The influence of loading is seen from the experimental points in Figure 8, which all refer to propellers designed according to the TMB method, Reference 24. Therefore, they all have similar strength characteristics. However, they do represent different, although typical, values of advance coefficient. Despite this the influence of loading is clearly to be seen. Also shown are estimations of efficiency for a family of typical propellers calculated according to the TMB method, Reference 24, which is known generally to overestimate efficiency, Reference 1, and as estimated by our own method, which takes into account the effect of wide-bladedness and back-wetting on sectional efficiency. These calculations have been carried out by Mr. R. Barr of HYDRONAUTICS.

In our opinion the strength of propellers designed according to Reference 24 may often not be adequate, so that generally thicker blades must often be utilized. Neither are such propellers designed to operate in strongly non-uniform flows, which require increases in the mean incidence of the elements in order to avoid face cavitation. For both of these reasons the efficiencies indicated in Figure 8 are not necessarily to be achieved in practice.

In the early stages of design a cruise advance coefficient must be selected. The achievable efficiency depends very much on this selection, which is usually based on a compromise between the interests of the gear and shaft designers and the propeller designer. Therefore the improvement of supercavitating propeller efficiencies in high speed applications depends not only on the solution of hydrodynamic problems but also upon mechanical developments.

The variation of propeller efficiency during heavily supercavitating operation at off-design conditions is of considerable importance for hydrofoil applications, as the possibility of running out of turbine power at take-off is by no means insignificant. The detailed calculation of off-design efficiency is not in general possible, but good estimations may be made. In fact, the behaviour of the efficiency is rather simple; at sufficiently low advance coefficients the supercavitating efficiency becomes essentially independent of the cavitation number and linearly dependent on J! This is illustrated in Figure 9, which is a schematic. This result, which has been found for many supercavitating propellers, is at first glance surprising, since at a given J, the thrust produced by the cavitating propeller depends a great deal on the cavitation number. There is, however, a simple explanation for this result.

At sufficiently low advance coefficients the production of thrust due to blade incidence will dominate the camber-produced thrust. The force acting on each blade element will thus very closely be normal to the line between the blade leading and trailing edges. This force decomposes into contributions to the thrust and torque whose ratio depends only on the blade pitch but not on the magnitude of the blade normal force; this ratio is thus independent of the inflow conditions. Under these conditions the blade efficiency becomes independent of cavitation number, and linearly dependent on advance coefficient. This result is indicated in the sketch inset in Figure 9, which shows, for simplicity, a flat-faced blade element.

THE MECHANISM OF OPERATION OF SUPERCAVITATING PROPELLERS

Subcavitating Propellers - Review

The observation in water tunnels of operating supercavitating propellers reveals the existence of substantial cavity formations, such as are shown in Figures 10a - 10d. Indeed, the existence of these large cavities was noted by Parsons some 70 years ago. These cavities are so large and their proximity to the blades so close that it would be really surprising should they not seriously affect the operation of the propeller. In fact, they cause the flow through a supercavitating propeller to be altogether different than for a subcavitating propeller. Let us review some of the things we know about the latter.

Usual subcavitating propeller blades are sufficiently thin so that the effect of their thickness on the flow is not in any way essential. The action of the blades is thus primarily due to their camber. They may thus be thought of as vortex surfaces composed of continuous distributions of vortex lines. These lines must of course be continuous in the fluid, so that they are shed from the blades into the propeller wake to form there one continuous trailing helical sheet per blade. The space behind the propeller is thus to a certain extent filled by shed vorticity. The latter may at each point where it exists be vectorially decomposed into longitudinal and circumferential components, which induce, respectively, rotational and axial velocities in the flow.

If the number of blades becomes very large and the chord of each very short, it becomes possible to represent the axial flow field due to the propeller by consideration only of the effect of the circumferential component of the shed vorticity. This vorticity may, in turn, be thought of as comprising a continuous distribution of concentric vortex sheaths. These are of a radius which contracts behind the propeller, but for light loadings this contraction may be neglected. The propeller blades themselves degenerate into a disc composed of essentially radial vortex lines. These induce equal but opposite circumferential velocities across the disc. The longitudinal shed vorticity induces angular velocities which exactly cancel out the influence of the disc at any point in front of or outside the propeller slipstream, where the flow, in view of its irrotationality, cannot possess angular momentum. The angular velocities just behind the disc are thus half due to the longitudinal component of shed vorticity and half due to the bound vorticity in the disc. The increase in angular momentum at any point across the disc is in reaction to and linearly related to the local torque on the blade system.

Simple momentum theories incorporate the axial flow system as described above plus an assumed discontinuity in flow stagnation pressure across the disc, but neglect the rotational flow in the slipstream — this may be shown to be a consistent procedure. Furthermore, in the case of light loadings it is possible to represent the flow field due to the trailing vortex sheath by a disc of sink singularities whose radial strength depends on the loading distribution, and the actuator disc rather than the vortex sheath picture is usually taken as the starting point of the momentum theory. Despite the usual neglect of rotation, the idealization of the propeller action introduced in the simple actuator disc model is fair enough in portraying the propeller as a device functioning continuously to accelerate fluid aft and to do useful work as a result of the reaction on the blades and shaft. The axial flow field is asymmetric when viewed from the propeller plane by an observer moving with the speed that prevails there. This asymmetry has as a consequence that the total increase in flow momentum, as observed in the wake far downstream where the pressure has returned to ambient, is just twice the increase in flow momentum as observed at the propeller disc. The pressure just behind the disc is, of course, greater than ambient and therein is stored half of the momentum eventually to be delivered to the slipstream. In view of continuity the flow velocity immediately in front of the disc is identical to the velocity just aft of it, but no work having been done on those fluid elements which have yet to pass through the disc, the increased momentum of the incoming flow has been realized at the expense of the pressure, which is suitably reduced.

In the absence of blade friction or form drag, the work done on an element of the flow on passing through the disc is simply he pressure increase across the disc times the velocity of the flow at the disc, say U_1, while the useful work done by the corresponding element of the propeller is simply the net thrust loading times the absolute forward velocity of the propeller, say U_o. The net thrust loading is also just equal to the head rise across the disc. The ideal efficiency is thus U_o/U_1. The pressure increase across the actuator disc, which equals the local net thrust loading, is also just equal to the gain in kinetic energy represented by the acceleration of the flow from far upstream to far downstream. As noted earlier, this pressure rise is also equal to the loss in rotational kinetic energy across the disc. These last facts allow the derivation of the result that the induced velocity at any point in the propeller disc is normal to the resultant relative velocity of a blade section.

A prediction of the actual thrust produced by a given propeller depends of course upon the hydrodynamic performance of the blades themselves, and this is usually predicted from two-dimensional theory or tests, suitably corrected for "wide-blade" or aspect ratio effects through the application of so-called "curvature corrections," see References 63 - 65. These are generally designed to compensate for the reduction in blade lift effectiveness due to spanwise changes in the blade and due to the flow spillage about the tip. A most noteworthy aspect of the situation for subcavitating blades is that the performance of the separate blade elements is hardly at all affected by the presence of the other blades, Reference 64. In other words, blade interference or cascade effects are of negligible importance. This is in sharp contrast to the case of supercavitating blades, as we shall see.

Cavity Blockage

The shed vortex field which we have described above also exists in the case of a thrusting supercavitating propeller, but superimposed upon this is an equally important field due to the cavities themselves. The latter flow may be thought of as due to cavity drag, while the former is due to thrust. The shape of cavities shed from a supercavitating propeller are highly variable; they depend upon the propeller thrust and efficiency, and upon the cavitation number. They may also depend upon tunnel wall effects - especially in the case of a completely closed water tunnel test section. These cavities originate in the plane of the propeller blades and extend downstream of the latter. Their length increases with decreasing cavitation number and becomes infinite for $\sigma_o = 0$. Generally, however, cavity lengths lie between 1/2 and 2 propeller diameters. By reducing the available flow area behind the propeller disc they cause the flow speed there to accelerate rapidly. In fact, they cause the flow speed behind the disc to take on a value which just corresponds to a flow pressure there equal to the cavity pressure.

The rotating cavities act in the manner of an obstacle to the flow approaching them and thus tend to retard this flow. The smaller the blade cavitational efficiency the stronger is this action. Due to this effect the accelerating action of thrust upon the approach flow may often be largely eliminated for a fully supercavitating propeller and it may not be uncommon for such propellers to operate with a net retardation of the inflow at the disc. It is clear that the usual subcavitating predictions of axial inflow are inapplicable; these facts are demonstrated by Equation [1], given later. On the other hand, the angular induced velocity at the disc is entirely torque dependent and may be calculated in much the same way for subcavitating and supercavitating propellers. Note that the net induced velocity at the disc of a supercavitating propeller is not normal to the relative blade velocity as it is in the subcavitating case.

For a subcavitating propeller, the ideal efficiency always takes on values less than unity. In the present case, however, the inflow may be retarded, and the ideal efficiency may thus assume values in excess of unity. This is, at first, startling to contemplate. However, it is well known that even subcavitating propellers operating in strong wakes (regions of retarded flow) may enjoy efficiencies greater than unity. In blocking the oncoming flow, the cavities on a supercavitating propeller create, in a sense, a wake ahead of the propeller and in this way an increase in ideal efficiency is caused at the expense of cavity drag or blade efficiency.

Thrust Deduction

Subcavitating propellers placed behind a hull normally cause an increase in the drag of the latter because of the falling pressure gradient (suction field) which accompanies the acceleration of the flow in front of the disc. This drag or so-called "thrust deduction" is often significant. In the case of a supercavitating propeller placed behind a hull the thrust deduction may be largely eliminated; this has been noticed experimentally, Reference 38 and 66. The thrust deduction may conceivably take on negative values, especially in the case of very close proximity of the hull and supercavitating propeller. This effect arises because of the flow retardation due to cavity blockage, as this retardation may result in net rising pressure gradients around the ships stern. In considering the combined effects of the thrust field and the drag (or cavity) field on the thrust deduction, it should be kept in mind that the spatial decay of these two fields directly ahead of the screw are different, the induced velocities due to thrust decaying in the far field like $(\text{distance})^{-1}$, while those induced due to drag decay like $(\text{distance})^{-2}$. It is thus conceivable that the flow might be retarded directly before the screw, but slightly accelerated at larger distances forward. For this reason there probably exists no very simple relation between the ideal efficiency and thrust deduction accompanying fully supercavitating operation.

Typical flow patterns accompanying sub-and supercavitating operation are shown in Figure 11. It is worthwhile to examine those carefully. The altogether different character of the supercavitating and the subcavitating cases is easily seen.

New Momentum Theory for Supercavitating Flows

The designer will be interested to know just how serious are the cavity blockage effects on the inflow, for he must accurately predict the latter if his design is to meet the specifications. I have recently derived a momentum theory suitable for fully supercavitating propellers which allows a prediction of the axial induced velocity at the propeller disc in terms of the non-dimensional thrust loading (C_T), the blade cavitation efficiency (η_c), and the free stream cavitation number (σ_o). An important result of this theory is:

$$\frac{U_1}{U_o} = \sqrt{1 + \sigma_o + C_T/\eta_c} - \sqrt{C_T(1 - \eta_c)/\eta_c} \qquad \underline{\text{supercavitating}} \ [1]$$

where

U_o is the free stream speed

U_1 is the axial speed at the propeller disc

σ_o is the free stream cavitation number, $p_\infty - p_c/\frac{1}{2}\rho U_o^2$

C_T is the thrust coefficient, $T/\frac{1}{2}\rho U_o^2 A_d$

η_c is the blade cavitation efficiency, η/η_i

η_i is the ideal efficiency, U_o/U_1

η is the net propeller efficiency.

This result may be compared with that from the usual (subcavitating) momentum theory:

$$\frac{U_1}{U_o} = \frac{1 + \sqrt{1 + C_T}}{2} \qquad \underline{\text{subcavitating}} \ [2]$$

Numerical calculations from Equation [1] for typical values of C_T, σ_o and η_c show quite clearly that the distribution of flow velocities and pressures which attend the operation of a heavily supercavitating propeller will not at all correspond to the predictions of theory for subcavitating propellers, as we have stated earlier. The use of the latter thus seem to us to be unjustified. Even for a relatively weakly supercavitating propeller it seems problematical that predictions of inflow speed based on subcavitating propeller theory are useful.

A number of other very useful facts may be deduced from this new momentum theory. It can, for instance, be shown that in an unbounded stream the cavity length is finite for $\sigma_o > 0$ and is infinite for $\sigma_o = 0$. The cavity maximum diameter is shown in the latter case to be finite only when the inflow and free stream speeds are identical. In the case of cavities of finite length, a loss of head occurs across the region of cavity collapse. The resulting head in the wake is still higher than the free stream head for a thrusting propeller and lower for a drag disc. The outflow speed just behind the region of cavity collapse is shown to be greater than the inflow speed for all cases of retarded inflow and for moderate degrees of accelerated inflow; for sufficiently large thrusts the reverse may be true. It can also be shown that no corrections to inflow speed are required for a supercavitating propeller operating either in an open jet or between solid walls; this is somewhat in contrast to the case of the subcavitating propeller for which inflow speeds must be corrected for the presence of solid walls. Finally it may be shown that conditions occur under which a supercavitating propeller will choke a solid wall water tunnel; that is, the cavity length will become infinite at non-zero cavitation number ($\sigma_o > 0$). All of these results should serve to convince us that in dealing with the design, testing, and operation of supercavitating (or ventilated) propellers we are faced with certain phenomena which have no counterpart in our previous propeller experience.

Blade Interference Effects

Supercavitating blades of the same propeller, unlike their subcavitating counterparts, interact with each other in a most serious way. In fact, as we have already discussed earlier, it is essential to take into account the interference between a blade and the cavity shed from the preceding blade in order to understand and explain the arched shape of the fully supercavitating characteristic curve (k_t vs. J). Furthermore, these effects generally occur not only during off-design operation, but at the design point too.

In order to understand the nature of blade interference it is conceptually useful first of all to depict the blade section as an element in a two-dimensional cascade, Figure 12, although we should not forget that the real connection between cascade and propeller flows is somewhat vague. For the high stagger angles (low pitch angles) usually utilized in supercavitating propellers, the largest part of the cascade effect would seem to be taken into account simply by allowing for the presence of a free surface beneath the blade element, Figure 13. This is much simpler to do than to deal with the cascade flow itself and as long as the cascade turning angle is small, leads to reasonably good agreement (for the hydrofoil force coefficients) with results from the cascade theory itself, as we show later (Figures 14 and 15). This simple theory is, furthermore, probably just as valid as cascade theory in application to propeller flows.

In a fully supercavitating propeller, the gap between the pressure face of each blade and the cavity shed from the preceding blade is not large relative to the blade chord. If the cavity is thin, then this gap — in ratio to the blade chord and measured normal to the chord — depends upon the ratio of the local advance ratio of the blade, and the local blade area ratio; as the cavity thickens, this ratio decreases. Thus,

$$\frac{\text{Gap}}{\text{Chord}} < \frac{U_o \cdot \cos\beta}{n\ B\ c} = \frac{\cos\beta}{\pi}\left(\frac{U_o}{nD_\ell}\right)\cdot\left(\frac{\pi D_\ell}{Bc}\right) \qquad [3]$$

where

U_o	is the free stream speed
n	is the rotative speed in rev./unit time
D_ℓ	is the local disc diameter at the section
B	is the number of blades
c	is the local chord
β	is the local pitch angle

As an approximation for the entire propeller, this may be written,

$$\frac{\text{Gap}}{\text{Chord}} < \frac{J}{\pi \cdot \text{BAR}} \qquad [4]$$

where J is the usual advance ratio
and BAR is the expanded blade area ratio.

It is thus clear that for usual supercavitating propellers ($J < 1.0$; $BAR > 0.3$) the gap-chord ratios for the blades are always less than 1.0. In fact, they are often less than 0.5.

When a supercavitating hydrofoil operates under a free surface at depth-chord ratios less than 1.0, it is well known that the performance characteristics of the hydrofoil are very much influenced by the proximity of the free surface, Reference 58. The same proves to be true when a hydrofoil operates above a free surface. The solution of the appropriate boundary value problem is given in Reference 56 for a flat plate hydrofoil at $\sigma = 0$, and the results are presented in Figure 14. The lift is increasingly reduced as the plate approaches the free surface, as is to be expected. For a cambered foil, the effect of the surface is not as pronounced, as is shown in Figure 15, which is based on unpublished theory and calculations. This fact can be taken advantage of in designing to mitigate the adverse effects of blade-cavity interference during off-design operation.

Also shown in Figures 14 and 15, for comparison, are results taken from more elaborate computations based on cascade theory and presented in References 67 and 68 (for the flat plate) and Reference 69 (for the cambered plate). The former of these utilizes exact theory and the latter two, linearized theory. Two of these theories (References 67 and 69) are based on a choked flow model, i.e. the cavitation number is not fixed in advance, but varies with the geometrical parameters (stagger angle, incidence, camber, and solidity) so as to produce an infinite length cavity. Other theory relating to choked cascade flows is presented in References 15, 70, and 71. The only detailed study of cascade flows with finite cavities has been carried out by Cohen and Sutherland, Reference 68, using linearized theory, and it relates to flat plate cascades.

The phenomena of cascade choking has implications for fully supercavitating propeller flows and is therefore important to discuss, although it is not likely to occur in propellers because of the relieving effects of the radial flow. Two-dimensional choking is most easily understood through reference to a non-lifting, or simple cascade such as a series of vertical plates arrayed at equal intervals - one above another. The flow around one of these plates is exactly like the flow around the same plate between solid walls which are separated by the same distance as separates the plates in cascade, Figure 16. The drag on the plate must result in a net axial momentum difference between the flow far upstream and far downstream. If the cavity pressure, p_c, is identical with the upstream pressure, p_o, then the velocities far upstream and far downstream are identical and no plate drag can be accounted for - nor, incidentally can the mass flow be balanced unless the cavity thickness vanishes. If the plate drag is not zero it is thus quite clear that the cavitation number corresponding to infinite cavity length must of necessity be greater than zero. Indeed, a simple relationship between choking cavitation number, σ^*, and the product of plate drag coefficient and plate spacing ratio may be derived:

$$C_D \cdot \left(\frac{c}{h} \right) = \sigma^* + 2 - 2 \sqrt{1 + \sigma^*} \qquad [5]$$

This is shown as Figure 16.

An increase in lift on the cascade element lowers the choking cavitation number as the net consequence of flow turning between far upstream and far downstream. The relations governing a choked cascade flow may be derived from momentum considerations and are:

$$C_D \cdot \left(\frac{c}{h_o} \right) = \sigma^* + 2 - 2 \cos \delta \sqrt{1 + \sigma^*} \qquad [6]$$

$$C_L \cdot \left(\frac{c}{h_o} \right) = 2 \sin \delta \sqrt{1 + \sigma^*} - \sigma^* \operatorname{ctn} \beta \qquad [7]$$

where

C_L is the lift coefficient

δ is the turning angle, see Figure 17.

β is the pitch angle, see Figure 17

and σ^* is the choking cavitation number based on the relative speed to the section.

The relieving effect of flow turning due to lift on the choking cavitation number is indicated in Figure 17. It is even seen to be possible to operate a turning cascade at zero cavitation number provided that the blade efficiencies (L/D) are suitably high. If $(D/L)^2 << 1$, then for $\sigma^* = 0$:

$$\frac{L}{D} = \frac{h_o}{c} \cdot \frac{4}{C_L} \qquad [8]$$

For smaller L/D's than given by [8], σ^* is greater than zero. With the aid of [8] it may be shown that a flat plate cascade typical of a supercavitating propeller is much too inefficient to operate unchoked at low but typical section cavitation numbers (several hundredths); even a cambered cascade is unlikely to operate unchoked down to zero cavitation number.

We have already commented that the radial flow that occurs in the flow through a propeller probably relieves the tendency toward cascade choking. It is nevertheless useful to understand the two-dimensional results, for they serve to convince us that we can not likely make estimates of the length or shape of the cavities shed from the blades on the basis of isolated flow results pertaining to the length and shape of cavities shed by the individual sections. On the contrary, the overall length and shape of the collective cavity or "bubble" behind the propeller disc is almost surely determined by the flow around the outside of that bubble together with gross characteristics such as thrust coefficient (C_T), forward cavitation number (σ_o), and blade cavitational efficiency (η_c).

The existence of cascade choking and a lower bound to possible cavitation numbers in the two-dimensional theory hampers us in its application to propellers, since theoretical predictions at suitably low section cavitation numbers may not therefore be attainable. Furthermore, the validity of a cascade model for a typical propeller flow is somewhat dubious. For these reasons and because of its much greater simplicity we very much favor the interference model based on a hydrofoil operating over a free surface. This model has in our experience proven to be very useful for the estimation of propeller section force coefficients.

Based on this model, the lift on a cascade element may be written:

$$L = \rho/2\ U^2 \cdot c \cdot \frac{\pi}{2}\ \alpha \cdot\ g\ (h/c) \qquad [9]$$

where

U is the relative speed to the element

α is the entering incidence

and $g(h/c)$ is a function which takes into account the effect of the gap in reducing lift (for $h/c \rightarrow \infty$, $g \rightarrow 1.0$).

It might be suggested, taking heed of Acosta's comments in Reference 69, that the correlation between this model and the real cascade flow might be improved by taking into account the turning of the flow in the latter, which tends to reduce the effective incidence of the flat plate elements. Thus, the effective angle of attack, α_{eff}, might be taken as the average of the incidence of the flow entering and leaving the cascade, or $\alpha_{eff} = \alpha - \delta/2$, where δ is the turning angle. The latter may be estimated from the following result, which may be obtained by equating the transverse force on the blade row to the rate of change of transverse momentum:

$$\delta \approx \frac{C_L \cdot \beta_o}{2} \qquad [10]$$

However, for low-pitch cascades such as are involved here, this angle is always small compared to the entering incidence, so that $\alpha_{eff} \approx \alpha$.

The validity of our approximations (at least relative to cascade flows) for low pitch angles may be judged by the correlation, presented earlier in Figures 14 and 15, between the lift effectiveness as calculated thereby with calculations according to both linearized and exact theories; the correlation is seen to be quite good enough for our present purposes.

Appropriate values of g(h/c) in [9] may be obtained from Figure 14. For the flat plate:

$$g_\alpha(h/c) \approx .50\ h/c \qquad \text{for } (h/c) < 1.0 \qquad [11]$$

This useful result allows a prediction of the highly non-linear lift curves of foils in cascade, as shown below.

The Fully Supercavitating Characteristic Curve

The parabolic or arched shape of the supercavitating characteristic curve (k_t vs. J) may now be explained. To do this we consider the performance of a flat plate cascade at a pitch angle typical for the outboard sections of a supercavitating propeller, as shown in Figure 18.

The flow entering between any two blades is conserved, so that:

$$w_o \cdot s \cdot \sin(\beta_o - \alpha) = w_1 \cdot h \qquad [12]$$

where it has been assumed that the flow between the plate and cavity beneath it is essentially parallel. For small σ_n, then $w_o \approx w_1$ and:

$$\frac{h}{s} \approx (\beta_o - \alpha)$$

or,

$$\frac{h}{c} \approx \frac{(\beta_o - \alpha)}{(BAR)} \qquad [13]$$

where it has been assumed that $\beta_c \approx \sin \beta_o$, i.e. that $\beta_o <$ about 30^o, as is usual over the most important part of the blade. Again, BAR is the propeller expanded blade area ratio.

In order to simplify the result further we may assume that $h/c <$ about 1.0, as is very often the case. Then, [9] becomes, using [11] and [13]:

$$\frac{L}{qs} \approx \frac{\pi}{4} \alpha \ (\beta_o - \alpha) \qquad [14]$$

The lift produced by the cascade thus reaches a maximum at an incidence equal to one-half of the section pitch angle, i.e. when $\alpha = \beta_o/2$. The maximum lift reached is:

$$\frac{L}{qs} \ (\text{max.}) \approx \frac{\pi \beta_o^2}{16} \qquad [15]$$

The maximum lift is seen, in this approximation at least, to be independent of the blade area ratio or cascade solidity.

The meaning of the result, [14], is that the decrease in blade-cavity gap which accompanies an increase in entering incidence (α) causes a loss in lift effectiveness which for sufficiently small gaps (corresponding to $\alpha > \beta_o/2$) more than offsets the increase in lift due to increasing incidence alone. This is the way in which the arched shape of the fully supercavitating thrust characteristic curve may be explained. We may, in fact, write:

$$k_t \approx \left(\frac{\pi^3}{8}\right) \cdot \frac{L}{qs} \approx \frac{\pi^4}{32} [\lambda(\beta_o - \lambda)]$$

or

$$k_t \approx 4\ k_t(\max) \cdot \left[\frac{\lambda}{\beta_o}\ (1 - \frac{\lambda}{\beta_o})\right] \qquad [16]$$

where we have neglected terms of the order $\beta_o{}^3$, where λ is J/π, and where,

$$k_t(\max) \approx \frac{\pi^4}{128} \cdot \beta_o^2 \qquad [17]$$

It would be surprising if this analysis, in addition to explaining qualitatively the observed behaviour of fully supercavitating propellers could be used as well for prediction, for many approximations have been made. For example, the change in propeller inflow which accompanies changes in the thrust and cavitational efficiency has been neglected. Nevertheless we have made a comparison between the experimentally determined fully supercavitating characteristic curve earlier presented in Figure 4, with the prediction according to [16]. The result is shown as Figure 19.

The Advantages of Camber

It is well known that the use of camber in supercavitating hydrofoils is essential for the optimization of the lift-drag ratio, Reference 20, and intensive quantitative studies of optimum foil design have been carried out taking into account the foil strength. (The latter is, incidentally, absolutely crucial to consider in any realistic comparison of foils, and conclusions reached in the absence of structural considerations are not likely to be meaningful).

Further, our preceding analysis of blade-cavity interference reveals the additional advantage of camber in improving the thrusting performance of fully supercavitating propellers during off-design operation. This advantage lies in the relatively milder effect of the cavity proximity in reducing lift due to camber in comparison to its effect on lift due to incidence, as is shown by comparison of Figures 14 and 15. Experience bears out theory in this respect, to the extent that larger maximum values of k_t are attainable with cambered blades than without.

The Effects of Blade-Cavity Interference at the Design Point

It seems crucial to consider interference effects in estimating performance not only during off-design operation but at the design point itself. In fact, we have found that lack of agreement, References 1 and 52, between experimental and predicted design thrust coefficients and efficiencies for supercavitating propellers designed according to the method of Reference 24, is very much reduced by the application of interference and blockage corrections to both thrust and efficiency. The interference corrections to the thrust take into account the reduced lift effectiveness caused by the proximity to the pressure faces of the cavity from the preceding blade, while the blockage correction takes into account the increased incidence due to reduced inflow speeds. These two effects act in opposite directions and often tend to cancel each other. This is,in our opinion, the reason why in the case of the first few supercavitating propellers designed and tested at the Taylor Model Basin such good results were obtained. However, these effects do not always negate each other, as in the case of the three supercavitating propellers tested at the NSMB, Reference 52. The agreement with design k_t was not good. When account is taken of interference effects in the prediction of k_t, however, good agreement is obtained as is shown in Figure 20. The latter is based on calculations carried out by Mr. R. Barr of HYDRONAUTICS. In these calculations curvature corrections derived from subcavitating theory were used and pitch corrections based on curvature corrections were utilized, as we believe is appropriate. The generally good agreement that we have obtained leads us to believe that supercavitating curvature corrections are unlikely to differ very significantly from the subcavitating case. The experience of Johnson, Reference 36, in his very successful application of the subcavitating Jones finite-span correction to low aspect ratio supercavitating wings further reinforces our belief. At any rate we cannot agree with Reference 1 in blaming the disagreement between conventional predictions and experimental values of thrust on incorrect curvature corrections. Rather we believe that most of the disagreement lies in the neglect of blockage and blade interference effects.

It is also now agreed, Reference 1, that experimental efficiencies at the design point consistently fail to attain the values predicted by the conventional design method, Reference 24. The explanation for this is not, in our opinion, to be found in any single weakness of the theory, but rather is due to a number of faults. First of all, and very important, a reduction of lift effectiveness whether in incidence or camber inevitably results in a proportionate reduction in lift-drag ratio. The reason for this lies simply in the fact that following a reduction of lift effectiveness an increase in incidence or camber must be employed to maintain approximately the same pressure distribution or lift; and since the drag is proportional to the product of the bottom slopes of the hydrofoil and the bottom pressures, the drag itself is consequently increased in proportion to the incidence or camber. The lift effectiveness of two-dimensional sections in isolated flow is reduced when these sections are employed in a propeller both on account of blade-cavity interference and finite span effects (the curvature correction). In fact, over the outboard regions of supercavitating propellers the lift effectiveness and resultant section efficiencies (L/D) may be reduced to 1/4 of the theoretical values for isolated flow. The conventional method of efficiency prediction does not take this reduction into account. A second important reason for disagreement between predictions and results lies in the usual assumption that the backs of the blades are not wetted and therefore do not suffer frictional resistance. It is a fact, Reference 1, that many supercavitating propellers do not in fact operate with cavities well clear of the blade backs. This is probably partly due to the incorrectness of the basic design procedure and partly to the employment of sections whose backs have been designed empirically. Mr. Barr of HYDRONAUTICS has estimated the design point efficiencies of supercavitating propellers taking into account by theory the loss of section L/D due to reduced lift effectiveness and assuming that the frictional resistance of the backs is 50 percent of that of the faces. The results are compared with experimental measurement from various sources and are seen to be in good general agreement.

We have been using a design method taking into account all of the factors discussed in the foregoing and have experienced good results. We are thus convinced that we have at least approached a good understanding of the mechanism of operation of fully supercavitating propellers.

SUMMARY AND CONCLUSIONS

The present paper is designed to serve a number of purposes. It contains a review of the historical background and development of supercavitating propellers. This review includes a discussion of the pioneering research of the Soviet scientist Posdunine and of the early work at the Taylor Model Basin, as well as a brief survey of other U. S. and foreign work carried out up to the present time. This paper also discusses in general terms the important operating features of supercavitating and ventilated propellers and some aspects of their design. Four regimes of propeller operation are defined: subcavitating, partially cavitating, supercavitating, and fully-supercavitating. Further, the partially cavitating regime is shown generally to be divided into two regions wherein the thrust either increases or decreases with increasing rotative speed. A non-ambiguous definition of supercavitating operation is given, as beginning where the rate of change of thrust with rotative speed is a minimum. It is shown how to present propeller data so as to allow rapid determination of the supercavitating regime of operation, and it is shown with a specific example that the supercavitating regime occupies a relatively small region of the complete propeller operating map. The characteristic arched shape of the fully-supercavitating curve (k_t vs. J) is described and explained in terms of blade-cavity interference. The relatively simple shape of the supercavitating efficiency curve at moderate and low advance coefficients is also described and rationalized.

An important purpose of this paper is to briefly describe the mechanism of operation of supercavitating propellers and especially to introduce some "new" hydrodynamic phenomena which are associated with their behaviour. By the latter I refer particularly to blade-cavity interference and cavity blockage. Taken together, these effects cause the flow about supercavitating propellers to be fundamentally quite different than the flow about subcavitating propellers. Cavity blockage even causes the inflow to a supercavitating propeller to be retarded, and may thus result in negative thrust deductions and ideal efficiencies exceeding unity. Blade-cavity interference drastically affects the lift effectiveness and profile efficiency of supercavitating blade elements. It is directly responsible for the arched shape of the fully-supercavitating characteristic curve (k_t vs. J) and thus for the poor thrusting ability of supercavitating propellers at very high rotative speed. Supercavitating cascades and choking are also discussed herein in connection with blade-cavity interference. Quantitative results pertaining to both cavity blockage and blade-cavity interference are given. The latter lend further importance to the use of camber, not only to optimize design efficiencies but also to improve off-design performance. Finally it is stated that performance predictions which take into account the "new" phenomena discussed herein are in good general agreement with experimental results, and some specific results of calculations are given. We conclude, therefore, that we have at least approached a good understanding of the mechanism of operation of fully-supercavitating propellers. At the same time it must be admitted that present theory is entirely inadequate to calculate many details of the flow about supercavitating propellers, and that a great deal of work therefore remains to be done.

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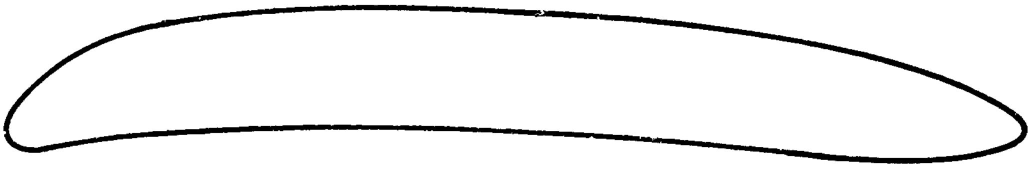

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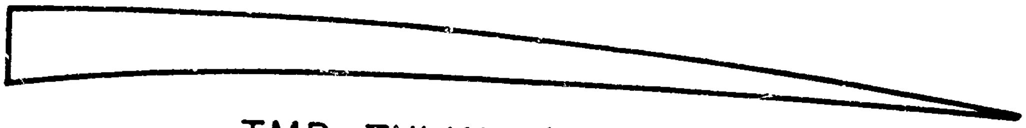

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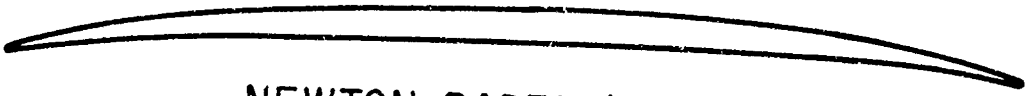

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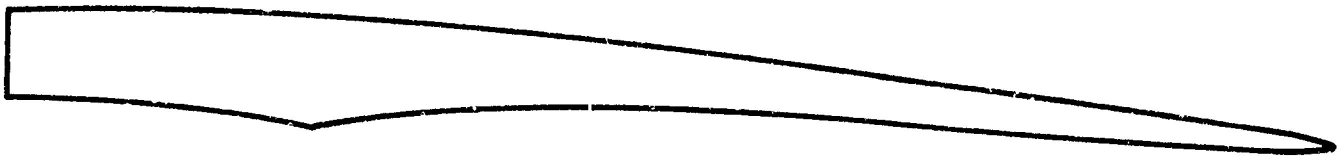

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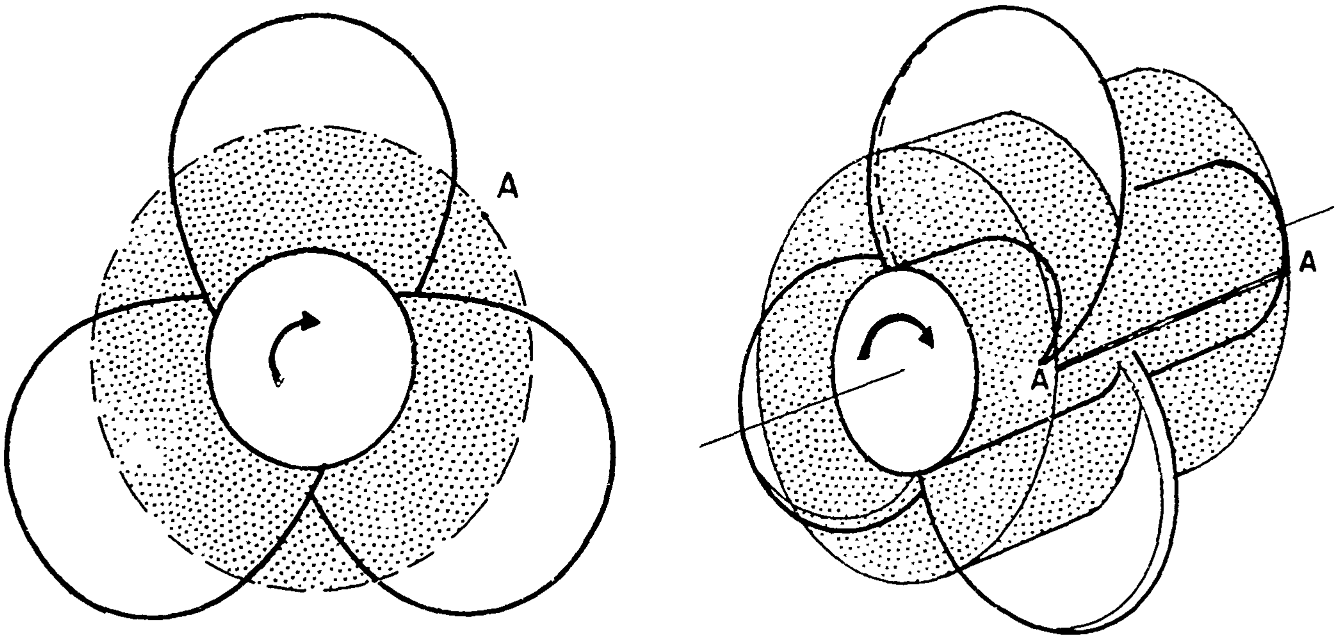
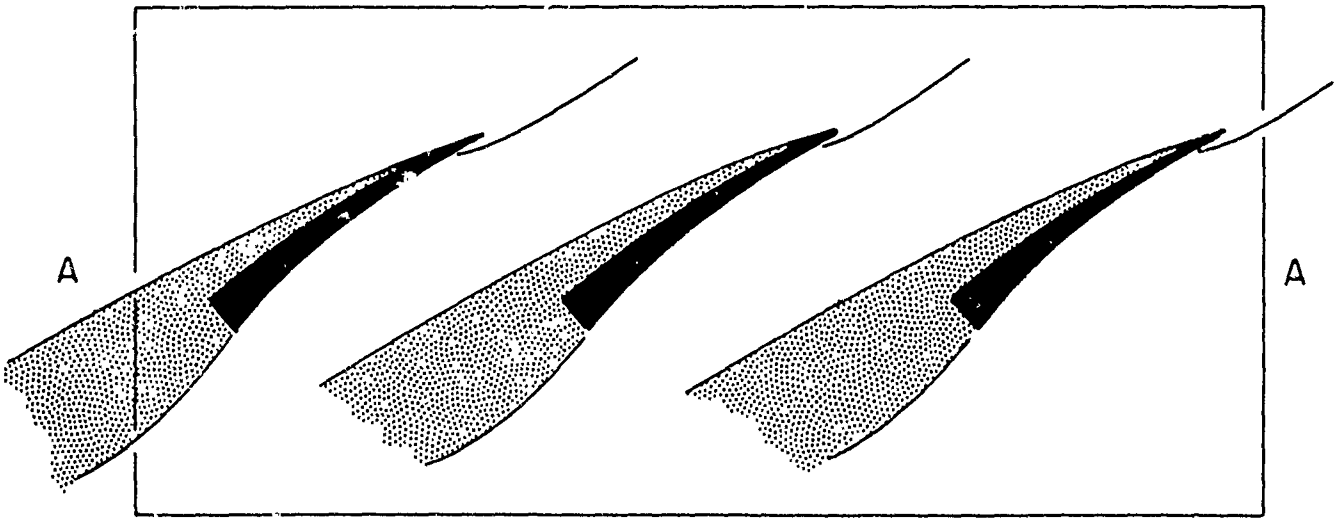
FIGURE 1 – SUPERCAVITATING PROPELLER PROFILES



FRONT VIEW – MARINE PROPELLER



TYPICAL CASCADE SECTION

FIGURE 12– CONVENTIONAL DEVELOPMENT OF A CASCADE SECTION

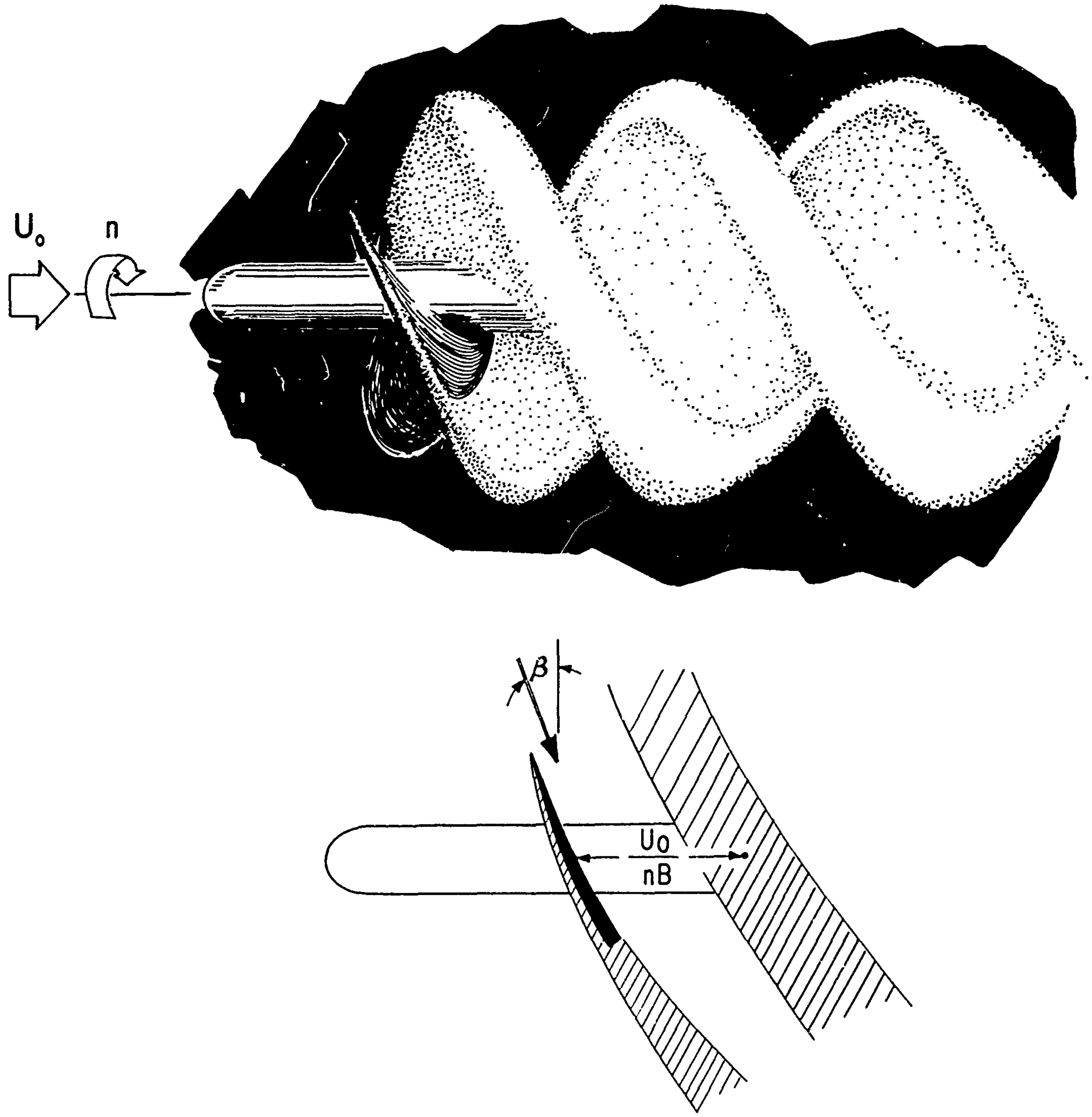


FIGURE 13 – INTERFERENCE BETWEEN SUPERCAVITATING BLADE AND NEIGHBORING CAVITY

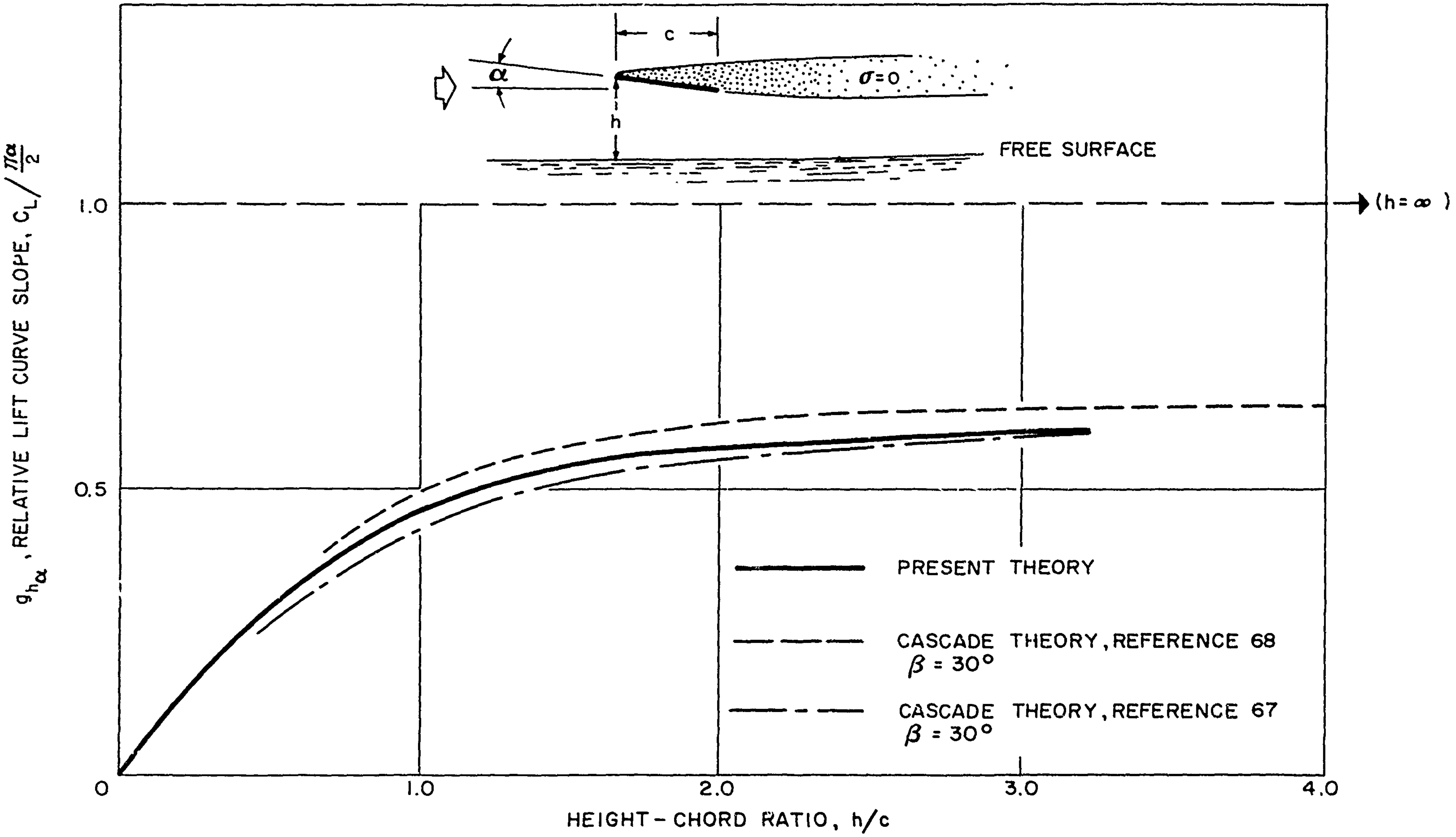


FIGURE 14– LIFT CURVE FOR A SUPERCAVITATING FLAT PLATE OVER A FREE SURFACE

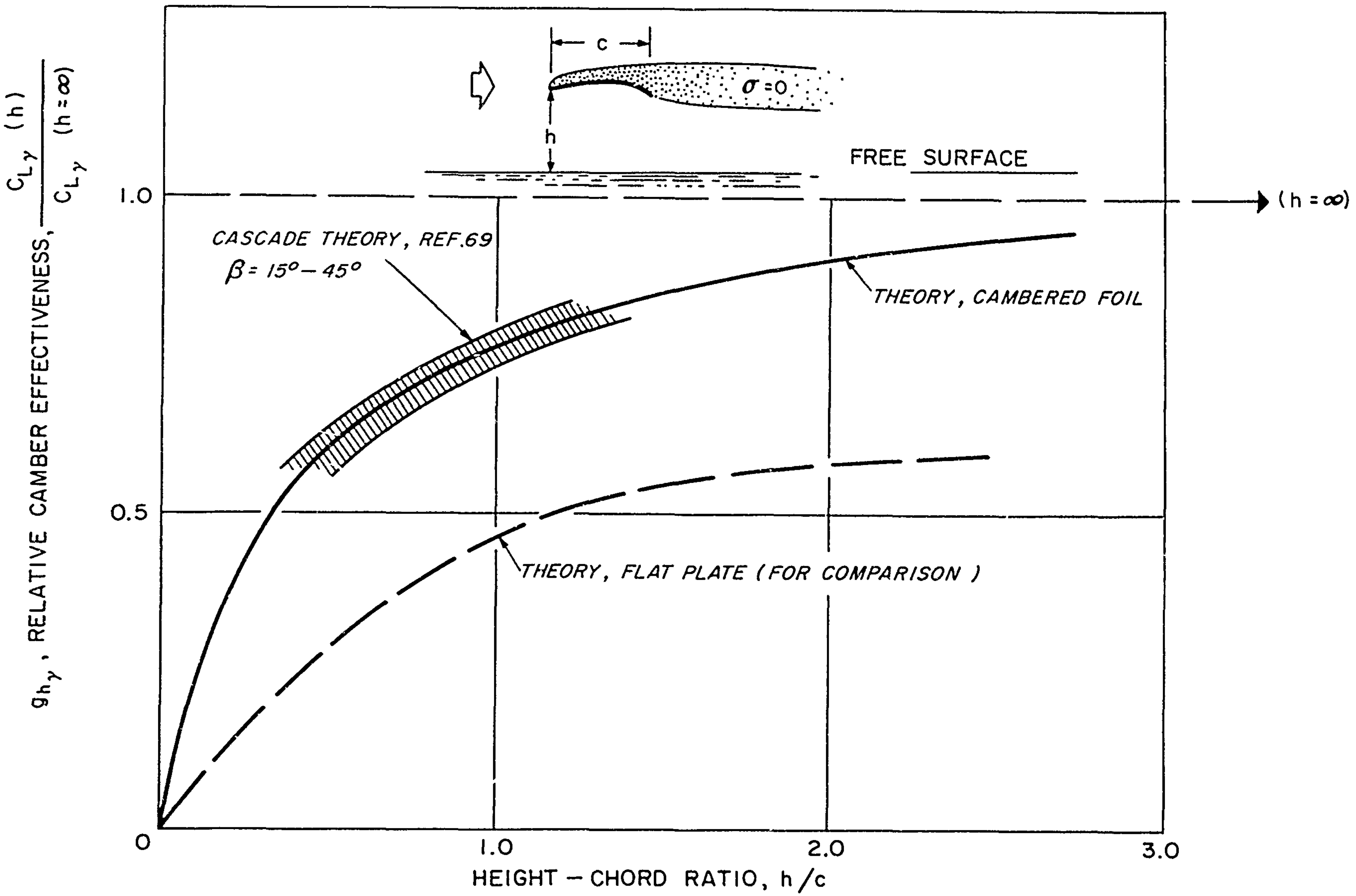


FIGURE 15– CAMBER EFFECTIVENESS FOR A SUPERCAVITATING FOIL OVER A FREE SURFACE

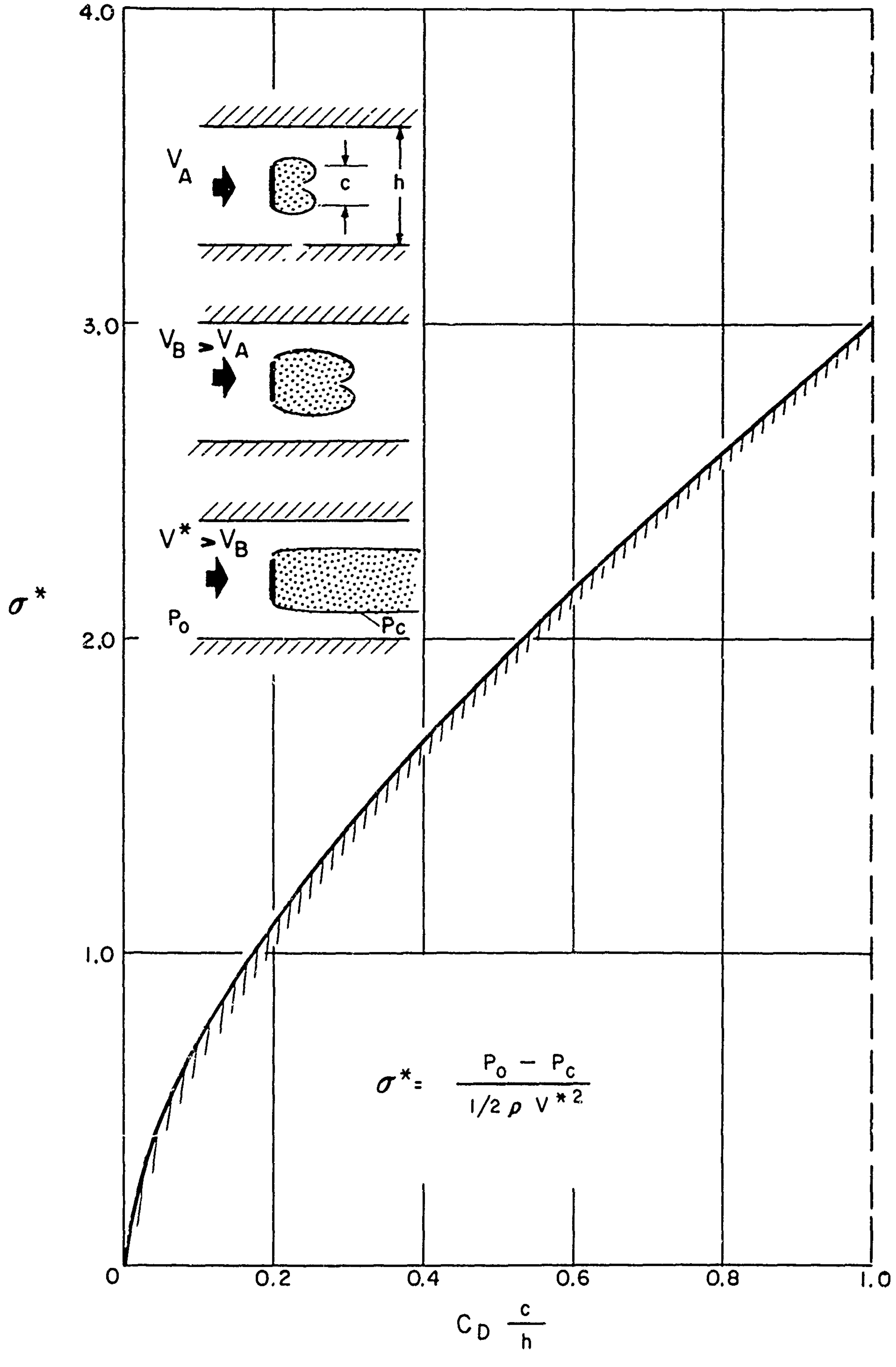
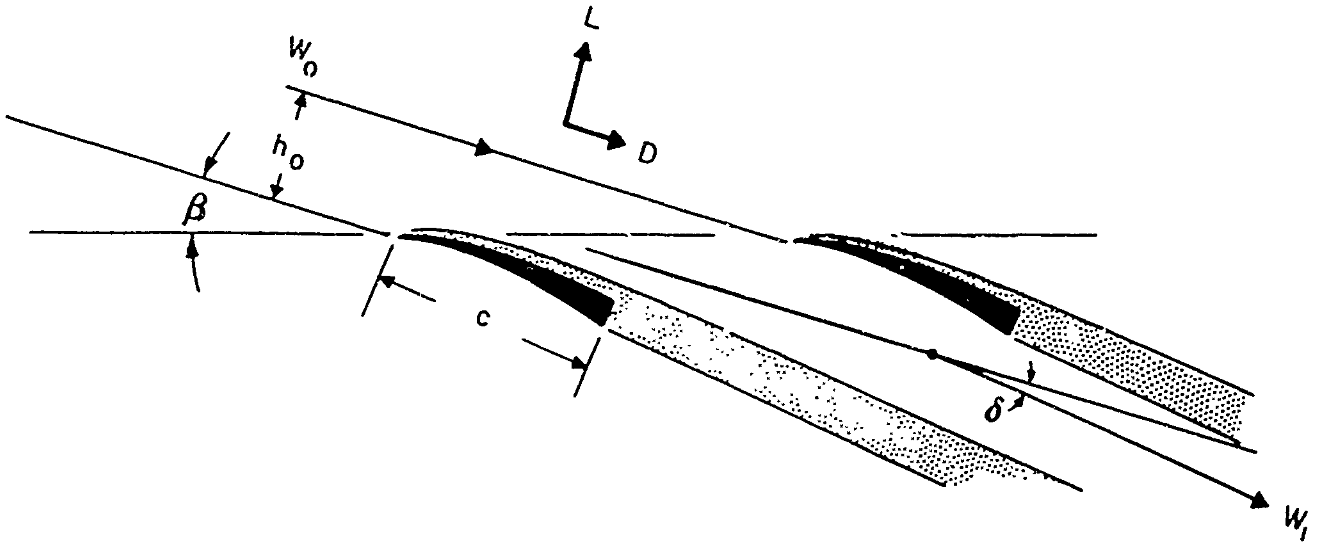
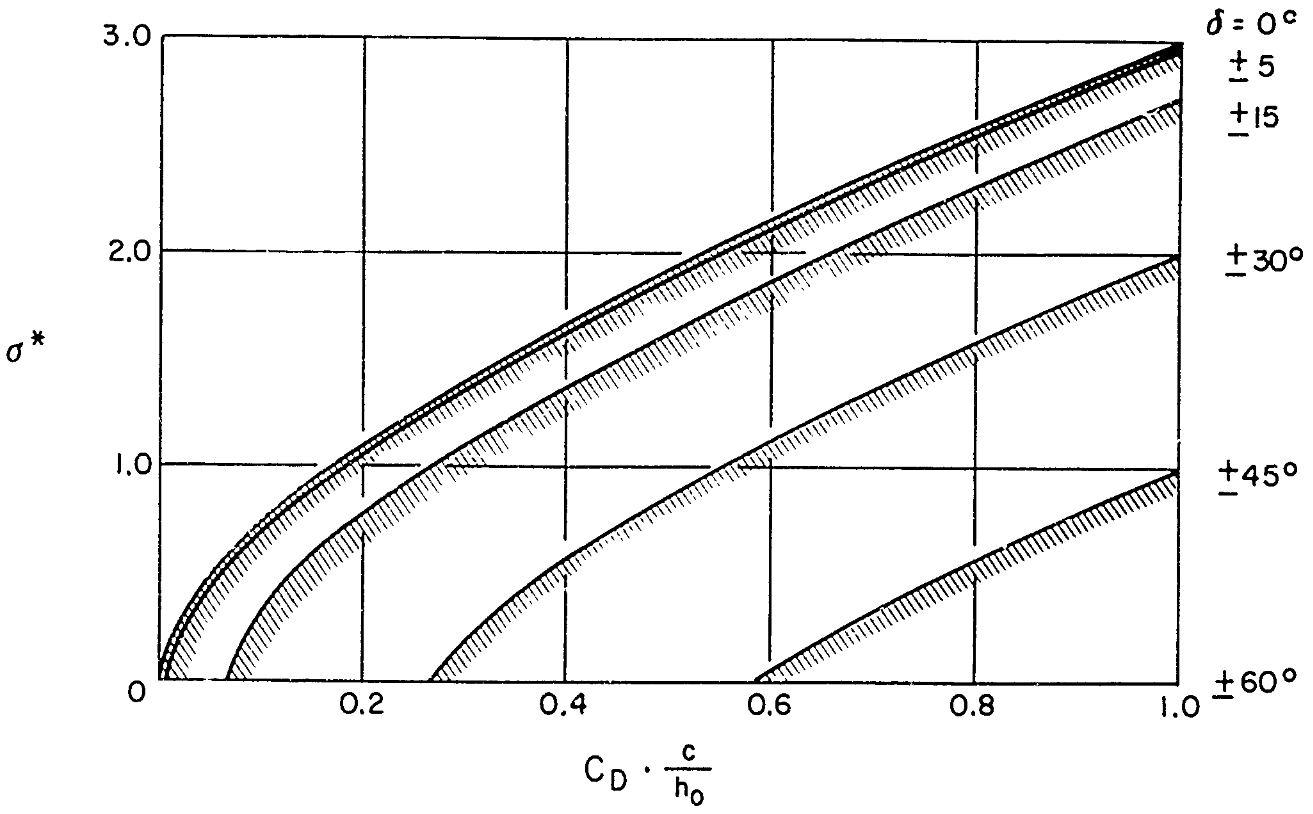


FIGURE 16– CHOKING IN A SIMPLE CASCADE



$$C_D \cdot \frac{c}{h_o} = \sigma^* + 2 - 2\sqrt{1+\sigma^*}\cos\delta$$



for operation at $\sigma^* = 0$: $\frac{L}{D} > 4\frac{h_o}{c}\frac{1}{C_L}$

FIGURE 17– CHOKING IN A LIFTING CASCADE

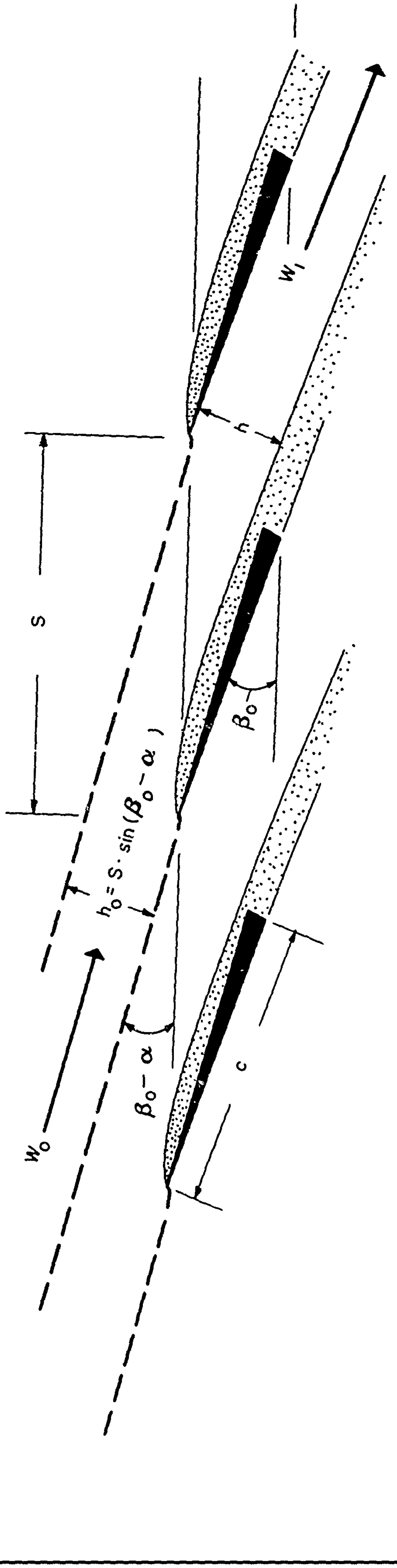


FIGURE 18- CASCADE SCHEMATIC

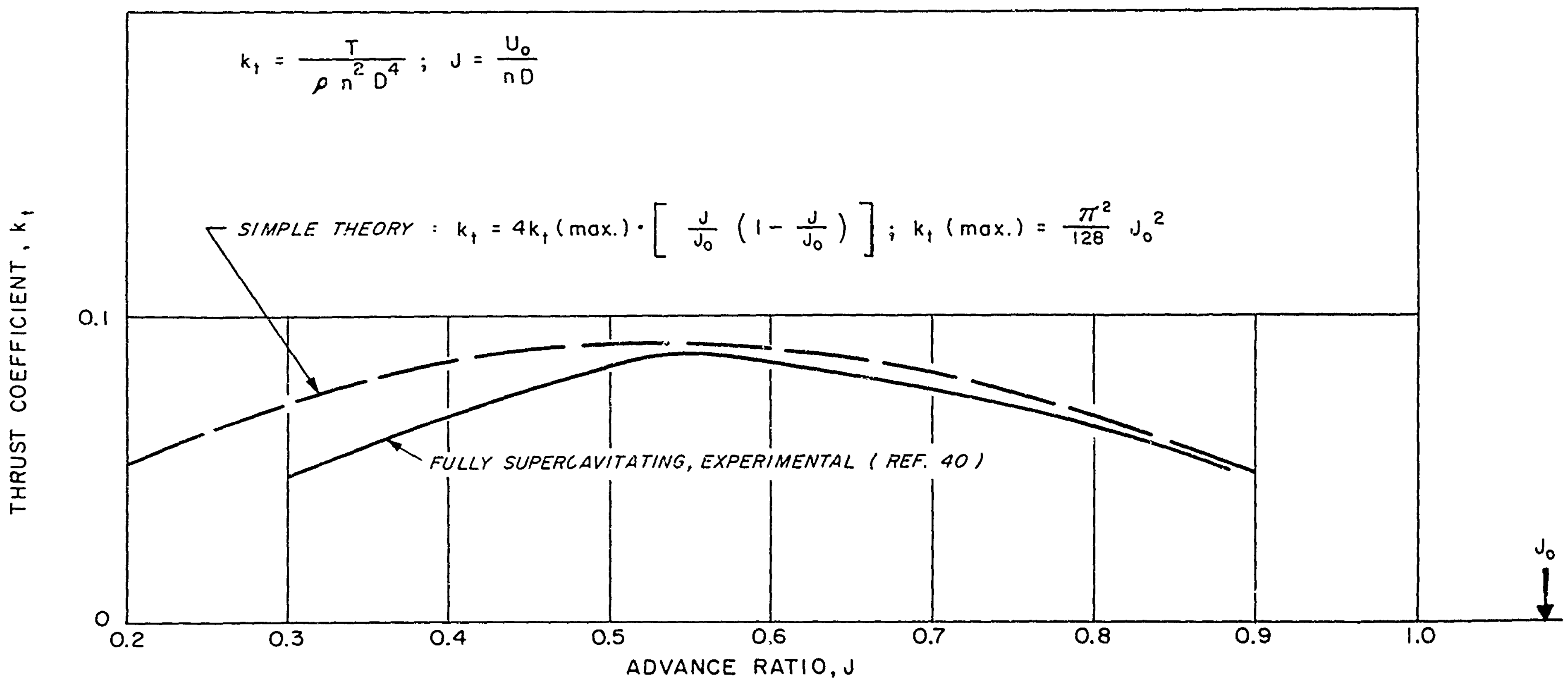


FIGURE 19– COMPARISON OF PREDICTED FULLY SUPERCAVITATING THRUST WITH EXPERIMENT FOR FLAT-FACED BLADES

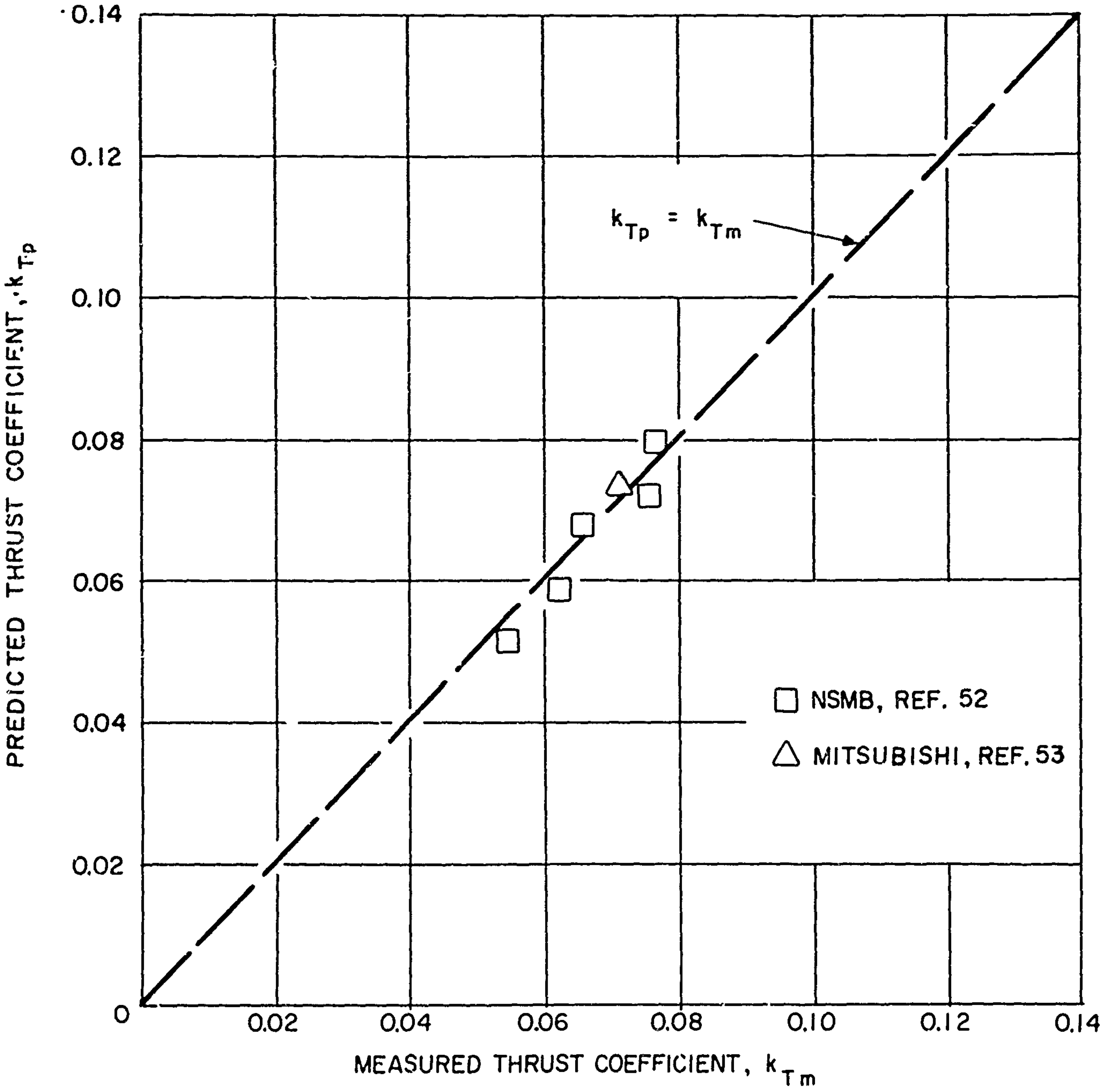


FIGURE 20 – COMPARISON OF PREDICTED AND MEASURED THRUST COEFFICIENTS

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