PROPELLERS AT HIGH SPEEDS

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The first NACA high forward-speed propeller tests were conducted during the recent war period. The purpose of these high-speed propeller tests was to study the factors affecting the propeller performance at high speeds and to obtain information permitting the design of propellers having high performance at high forward speeds. The purpose of this paper is to present the more recent results obtained in this program. Studies have been made of air flow phenomena at low speeds, which are therefore not included in this paper, of some of the basic factors which affect high-speed propeller performance. These studies cover research on propeller pitch distribution (reference 1), propeller design and performance (references 2, 3, and 4), dual-rotation propellers (references 5 and 6), and the field of flow around air inlet cowlings and propeller spinners (reference 7).

The results of the tests of the NACA 4-508-03 propeller in the Langley 8-foot high-speed tunnel are presented in figure 1 which shows the status of the high-speed research program on propellers. In the upper part of this figure is a plot of maximum efficiency against forward Mach number. The design numerals represent, in order of presentation, the propeller diameter, the design camber in terms of design lift coefficient at the 0.7 blade-radius station, the thickness ratio at the 0.7 blade-radius station, and the solidity per blade. These test results were obtained for a blade-angle setting of 60°. For purposes of comparison there are included in this figure the efficiency characteristics of propellers currently in use at the time the high-speed propeller program was initiated. Also included, for purposes of comparison, is the variation in ideal jet-propulsion efficiency based upon typical values of the thrust per unit area currently used in jet engines. Comparison between the previous propeller efficiency and the NACA high-speed propeller efficiency indicates the gains made in the early phase of the research program. It should be noted that the levels of efficiency for the NACA propeller at low speeds is unusually high, well in excess of 90 percent. The results indicate that propellers with relatively high levels of efficiency could be designed for speeds as high as 500 miles per hour. These high levels are the result of using optimum NACA 16-series propeller airfoils with very thin sections, of eliminating the thick shank sections of propellers, and of designing the propeller to operate with ideal Betz loadings by methods outlined in references 8 and 9. Comparison of this efficiency with the efficiency of typical previous propellers indicates the gains in propeller performance thus obtained by improved

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design. The onset of compressibility effects was delayed by about 100 miles per hour in forward speed.

The early phase of this research program was limited in forward Mach number to approximately 0.7 (approximately 500 miles per hour) and this limit is indicated by the cross-hatched region in figure 1.

A recent phase of this work has included the extension in the Langley 8-foot high-speed tunnel of this study to higher forward speeds in excess of 90 percent of the speed of sound. The part of the curve to the right of the cross-hatched region represents the results of these tests (reference 10). The purpose of the tests was to obtain data at extremely high forward speeds and increased power loadings for a study of the phenomena in this speed range and thus to define for modern propellers the maximum efficiency characteristics and to obtain indications of possible further improvement in propeller performance.

The test results show that, at forward Mach numbers in the order of 70 percent of the speed of sound, very large serious adverse effects of compressibility occur so that efficiency levels of the order of 50 percent to 55 percent are reached at forward Mach numbers of 85 percent of the speed of sound. Thus, for the first time, a comparison is obtained which defines the range of forward speeds in which propellers are more efficient than jet engines and the range of speeds in which jet engines are more efficient than propellers. It should be noted, however, that this comparison between the ideal jet efficiency and the propeller efficiency is subject to changes, as illustrated by the fact that large improvement over the previous propeller characteristics has already been obtained.

The second part of figure 1 is a plot of the power coefficient corresponding to the maximum efficiency curve for the two-blade NACA propeller shown in the upper part of the figure. Of interest here is the fact that the effects of compressibility on the power coefficient corresponding to maximum efficiency does not lead to very serious and abrupt reductions in the value of this power coefficient, which reduction will be shown later to occur at lower settings of the blade angle. As a matter of fact, at the maximum speed shown there is a tendency toward further increases in this power coefficient. Tests made at higher speeds where maximum efficiency was not obtained indicated moreover that at these higher speeds further rapid increases in the power coefficient can be expected. Predictions based on low-speed information of the power coefficient for maximum efficiency for the high advance-diameter

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ratios (approximately 4) associated with blade angles of 60° are thus indicated to underestimate the high-speed value of the power coefficient.

The lower part of figure 1 illustrates some of the reasons for the aforementioned changes. It is a plot of the radial distribution of thrust along the blade radius measured by momentum surveys. At low speeds the distribution of thrust very closely approaches the ideal loading for which the propeller was designed. As the forward speed is increased, however, effects of compressibility lead to loss in thrust, first at the tip, and, with further increases in speed, these losses progressively move toward the root section of the propeller. This type of phenomenon has been illustrated before at lower advance-diameter ratios (references 11 and 12). As this loss progressively moves inboard, however, another phenomenon begins to occur at the tip at these high blade angles and results in increased tip loads. This increase of load at the tip compensates for the loss in load at the inboard sections. Indications of this effect have also been found in flight (reference 13).

The increased load at the tip sections of the propeller is believed to be associated with the second force-break characteristic shown to occur for wings and airfoils in the transonic-speed range where, in plots of wing lift coefficient for constant angles of attack against Mach number, there is an abrupt rise in the lift values following the well-known loss in lift characteristics (reference 14).

The resultant section Mach number has been calculated for a large number of these measured thrust distributions for the points along the blade radius where the loss in thrust between the low-speed thrust value and the value at any high speed is the maximum. The resultant Mach number for all cases tends to scatter closely around a value of the resultant section Mach number of 0.9.

It is believed that, with such thrust distributions as were measured for forward Mach numbers of 0.85, the aforementioned losses in efficiency for these speeds may include a large component of induced loss because of the departure from the ideal loading (as indicated by a comparison of the low-speed and the high-speed thrust distributions). Modification of pitch distribution, for example, to provide a closer approach to the ideal type of load distribution may offer considerable improvement in the efficiencies shown.

Calculations have further indicated that a large part of the induced losses which may occur at these high forward speeds and high advance-diameter ratios can be expected to be associated with induced rotational losses. Thus the use of dual-rotational propellers which theoretically at least eliminate the rotational losses are indicated to offer improvements in propeller efficiency.

The use of sweep to delay the onset of compressibility effects to even highor forward speeds is also currently being studied. Preliminary tests with sweep incorporated in just the tip section of propeller blades has indicated that the use of sweep will permit a significant delay in the onset of compressibility effects (reference 15). More recently the NACA found that there were propeller blades incorporating sweep which had been built for flight tests by a manufacturer. It appeared that these blades would be available sooner than existing NACA designs which are currently being built. Steps were taken to procure these blades for testing in the Langley 16-foot high-speed tunnel.

Figure 2 describes the propellers and the test results obtained. Two propellers were tested, one straight and one with sweep as indicated by the plan-form lines. The part below the propellers is a plot of the variation of sweep angle along the radius of the swept propeller. The results of the tests are shown in the lower part of this figure in the form of maximum efficiency plotted against resultant tip Mach number which is chosen rather than forward Mach number since the resultant tip Mach number is a more exact indication of the onset of compressibility effects. The differences in maximum efficiency between the straight and swept propellers shown are within the experimental accuracy of the tests. The results show that sweep can be incorporated throughout the blade radius without serious adverse effects on low-speed efficiencies. Even at the maximum tip speed attained, which was a limitation imposed by the larger diameter (13 ft) of this propeller as compared to the standard size (10 ft) for which the dynamometer equipment was designed, there were no essential differences in the propeller efficiencies. Presumably, delays in the onset of compressibility effects might be indicated at higher tip Mach numbers. Because no effects of compressibility are shown, the magnitude of the delay from the amount of sweep used has not been defined.

Included in the part just under the blade plan-form curves for the two propellers to indicate the amount of sweep required for a given delay of compressibility effects is the variation in sweep indicated by analytical studies to be required to delay compressibility effects by approximately 100 miles per hour. These values indicate that large amounts of sweep are necessary before significant delays in the onset of compressibility effects can be realized. This same characteristic has already been shown for wings where

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sweep angles of less than 30° are not effective in delaying compressibility effects.

In addition to the recent work performed to study the phenomena on propellers at speeds in excess of 500 miles per hour, there has been made concurrently with the work just discussed a study at speeds up to 500 miles per hour in the Langley 16-foot high-speed tunnel of the effects of various design parameters on propeller performance (references 16, 17, 18, and 19).

Included in this work is the effect of solidity. These results are shown in figure 3 for studies of three propeller configurations. Tests were made of a two-blade narrow propeller, a two-blade wide propeller having increase in solidity of 50 percent over the narrow blade propeller, and a three-blade propeller utilizing the same narrow propeller blade, thus providing again a 50-percent increase in propeller solidity. The results are presented in the upper part in the form of a plot of maximum efficiency against resultant tip Mach number for a blade angle of 45°. It is indicated that little or no changes in efficiency occur in increasing the solidity by increasing the number of blades or the blade width. As a matter of fact, the changes in efficiency shown correspond in magnitude to the calculated changes in efficiency due to the increased induced losses occurring for the higher solidity propellers.

The lower part is a plot of the power coefficient corresponding to the maximum efficiency curves presented above. At low tip speeds the three-blade propeller absorbs considerably much more power at maximum efficiency than does the two-blade wide propeller. Thus an increase in solidity by the use of an increased number of blades is indicated to be more effective in increasing the power capacity of the propeller than is an increase in solidity by increasing the blade width. for fixed blade angle!!

At high tip Mach numbers where the effects of compressibility are shown to be severe, very large reductions in the power coefficient for maximum efficiency for all three propellers tested was observed.

These curves, which are presented for blade angles of 45° (advance-diameter ratio of approximately 2), are in marked contrast to the power coefficient curves for maximum efficiency shown in figure 1 where for blade angles of 60° (advance-diameter ratio approximately 4) no such large losses were shown.

The large variation in these power-coefficient characteristics at the high tip Mach numbers together with the differences at different advance-diameter ratios indicates that predictions of these

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characteristics based on low-speed data could be expected to be inaccurate. However, in order to attain even the maximum efficiency shown at the higher tip Mach numbers, it is necessary to operate at or very near these power coefficients because the results indicate that departure from these power coefficients would lead to efficiency values considerably less than the maximum values shown.

The onset of compressibility effects for the wide-blade propeller occurs at a higher tip Mach number than it does for the three-blade propeller. This difference is believed to be a result of the effects of aspect ratio, the wider blade having the lower aspect ratio. Reductions in aspect ratio have been shown in studies of wings by Stack and Lindsey to lead to delays in the onset of compressibility effects (reference 20). Increase in solidity by use of wide propeller blades has been studied through a range of solidities approximately twice that presented in figure 3 (reference 21). The results of these tests have given similar indication that wide propeller blades tend to delay the onset of compressibility effects.

Airfoil and wing studies at high speeds have long indicated that reductions in airfoil thickness ratio provides delays in the onset of compressibility effects. Studies of propeller airfoil sections (reference 22) have indicated that increased values of efficiency even at low speeds can be obtained through the use of thinner propeller sections. Tests of propellers having different thickness ratios have been studied to evaluate these effects in terms of propeller performance.

Figure 4 includes test results of two sets of propellers having different thickness ratios. A pair of propellers having the plan form shown on the left of the figure and having identical camber ($C_{L_D} = 0.3$), but with sectional thickness ratios of 12 and 8 percent, respectively, were tested. The distribution of the thickness ratio along the propeller-blade radius is shown. The maximum efficiency for these two propellers is plotted against a tip Mach number. The results indicate that even at low speeds, as was indicated by the airfoil studies, the thinner propeller has the higher efficiency and this incremental efficiency becomes considerably larger above tip Mach numbers of 0.92. Moreover, the point at which the effects of compressibility begin to occur are shown to be delayed by the thinner propeller.

On the right-hand side of the figure, test results are shown for another pair of propellers having identical characteristics but with thickness ratios of 5 and 6 percent, respectively, at the 0.7 blade-radius station. The variation in the thickness ratio

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along the blade radius is shown. In the plot of maximum efficiency characteristics, the thinner blade is the more efficient which, at the highest tip Mach number presented, amounts to an improvement in efficiency of approximately 2 percent and, at the same time, indicates further delays in the compressibility effects. For example, up to tip Mach numbers of 0.97, the 5-percent-thick propeller shows no adverse effects of compressibility; whereas the 8-percent-thick propeller in the left-hand part has shown effects of compressibility at tip Mach numbers in the order of 0.94. Thus, reductions in propeller thickness ratio to as low as 5 percent are shown to offer improvements in propeller efficiency.

Recent high-speed research on propeller airfoils in the Langley 24-inch high-speed tunnel has included studies of the effect of camber as well as effects of thickness ratio (reference 22). The effects of camber at high speeds, as indicated from this airfoil data, is shown in figure 5 in which is plotted the section efficiency of two propeller airfoils having the thickness, differing only in design camber (NACA 16-506 and NACA 16-106). The section efficiency is calculated from the equation shown in the figure and is a function only of the L/D characteristics of the section. The values of L/D for the two airfoils were chosen at a lift coefficient of 0.5 which is the design operating condition for the higher cambered airfoil. The results have been plotted against section Mach number.

At low speeds, as would be expected, the higher cambered airfoil when operating at its design lift coefficient of 0.5 is approximately 2 percent more efficient than the lower cambered airfoil. However, at high speeds the comparison is reversed, the lower cambered airfoil being 2 percent more efficient than the higher cambered airfoil even though the lift coefficient is considerably in excess of the design value for the low cambered airfoil. Data for other thickness ratios and for other airfoils have also indicated the same trend, and the results indicate that at supercritical speeds the most efficient airfoil sections are those which have very small amounts of camber or no camber. Thus, improvements in propeller performance is indicated through the use of reduced camber, particularly in the tip section of propellers where the sections are often designed to operate at supercritical speed conditions.

High-speed propeller tests of propellers having variations in camber have substantiated this conclusion in general, and figure 6 shows the results of a series of tests on three propellers differing only in camber. The propeller-blade form is shown in the figure, and the variation in the design lift coefficient along the blade radius is also shown for the three propellers. The test results are plotted in the form of maximum efficiency against tip Mach number. The highest values of efficiency at low Mach numbers are shown for the propeller having camber corresponding to design lift coefficient of 0.5. The propeller blade having a design lift coefficient of 0.3 is, at low tip speeds, only a few percent less efficient than the propeller blade having a design lift coefficient of 0.5. The propeller blade having a design lift coefficient of 1.0 shows the poorest efficiency throughout the range. At supercritical tip speeds, however, there is a tendency toward reversal of the comparison between the propellers having 0.5 and 0.3 design cambers, the lowest cambered blade having slightly the best efficiency. The effect is not as strong as was indicated by the study of propeller airfoils.

The results of the propeller airfoil study are somewhat masked by the fact that there exists a Mach number gradient all along the propeller-blade radius so that the effect of supercritical-speed operation is confined to the tip portions of the propeller, and thus the full effect of the improvement in efficiency through reduction in camber at supercritical section speeds is confined to a small portion of the propeller. At higher advance-diameter ratios where the Mach number gradient along the blade is more uniform, this effect would be expected to be larger.

High-speed propeller research has thus indicated that propellers having high levels of efficiency up to forward speeds in the order of 500 miles per hour are possible; that improvements in propeller efficiencies at speeds in excess of 500 miles per hour are indicated through the use of pitch distribution modifications and dual-rotation propellers; and that more extensive increases are possible through the use of sweepback and perhaps low aspect ratio in propeller blades. However, experimental studies to define the magnitude of these effects have not been made. The proper selection of camber, solidity, and propeller-section thickness ratio has also been shown to effect significant improvement in propeller performance.

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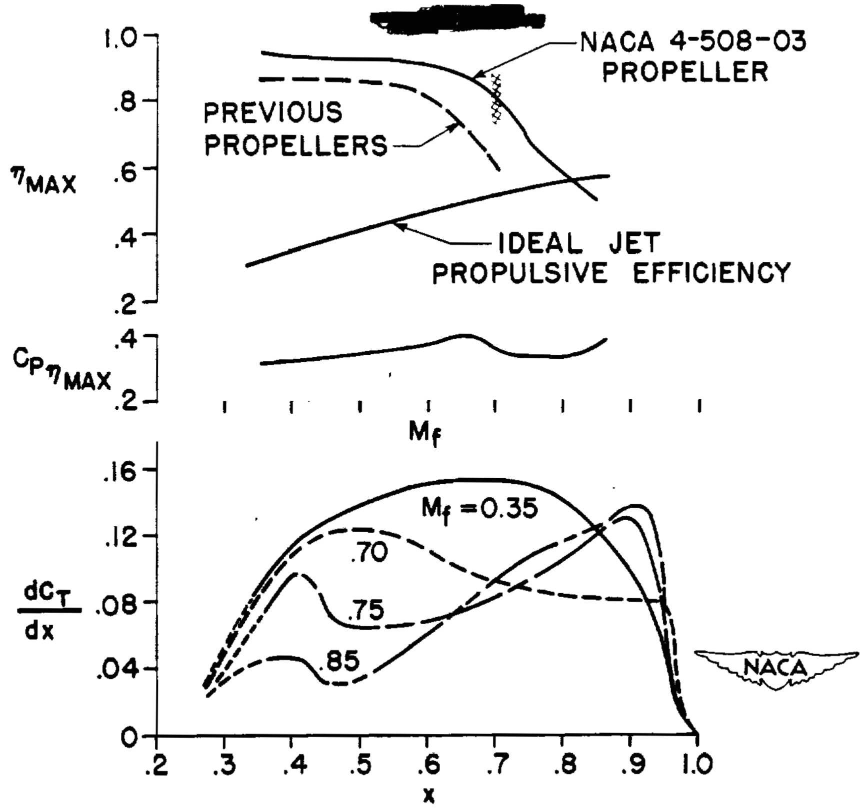
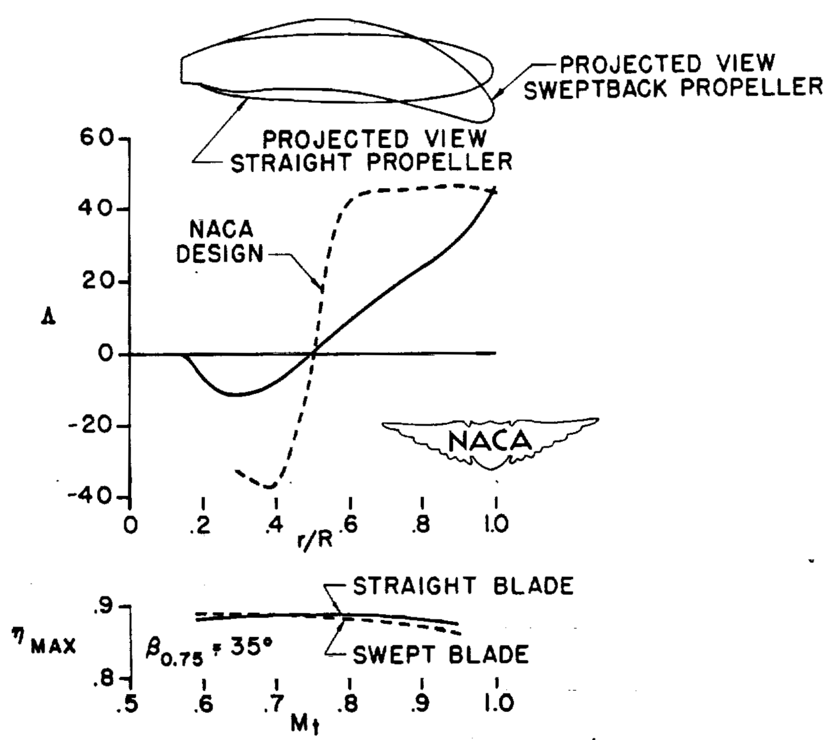


COMPRESSIBILITY EFFECTS ON PROPELLER CHARACTERISTICS OF NACA 4-508-03 PROPELLER $\beta = 60°$

Figure 1.



SWEPTBACK PROPELLER

Figure 2.

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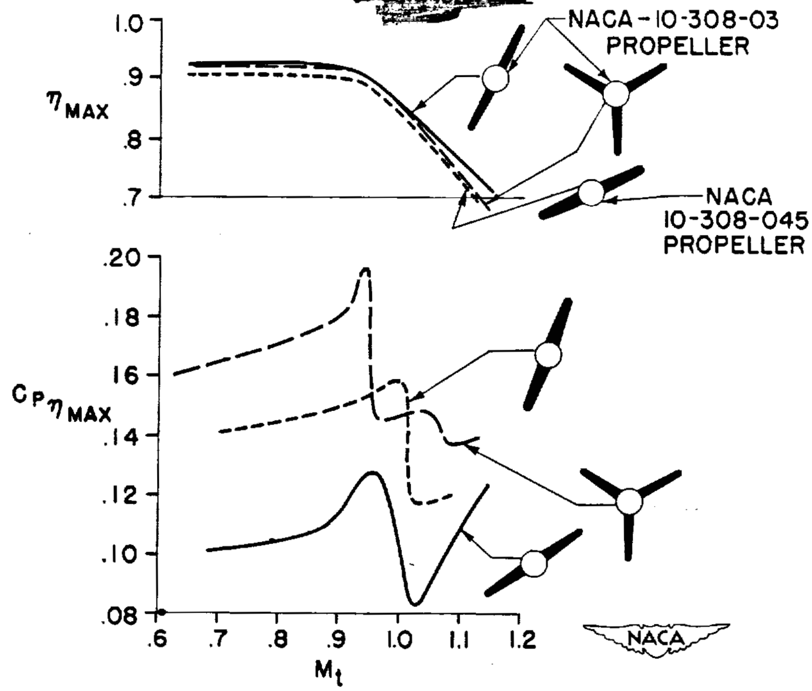
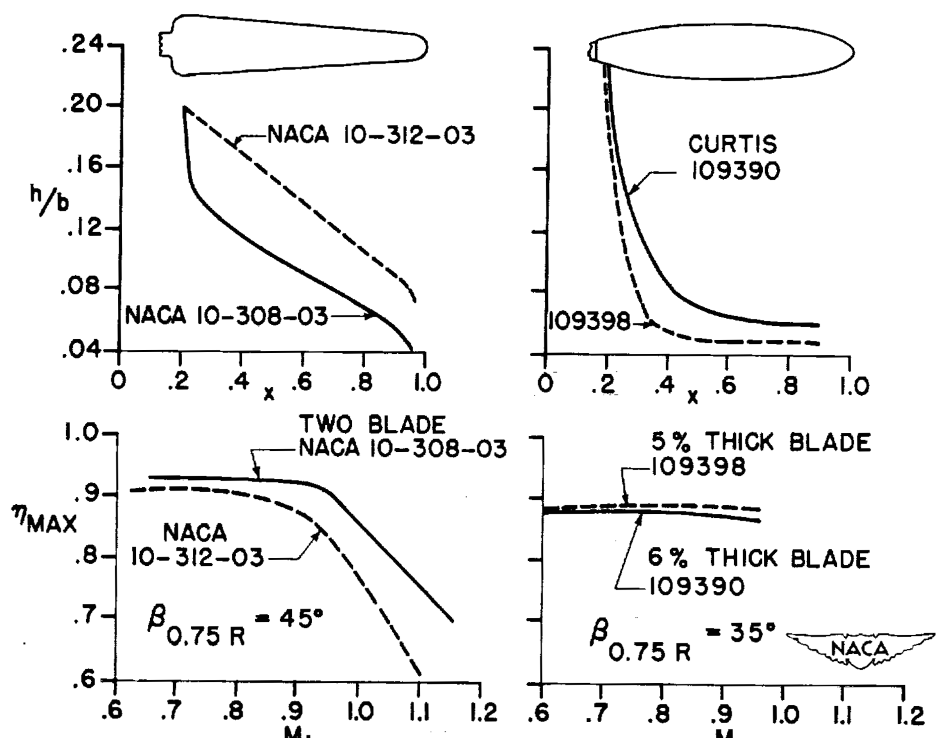


EFFECT OF SOLIDITY ON PROPELLER CHARACTERISTICS

$\beta_{0.75R} = 45°$

Figure 3.



EFFECT OF THICKNESS RATIO ON PROPELLER CHARACTERISTICS

Figure 4.

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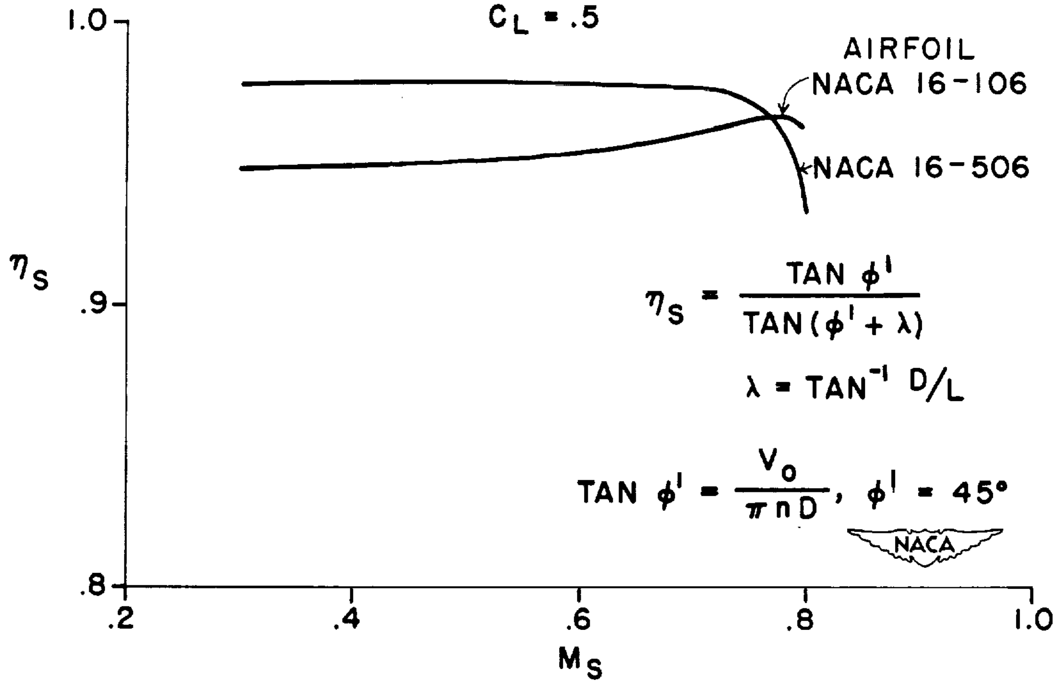
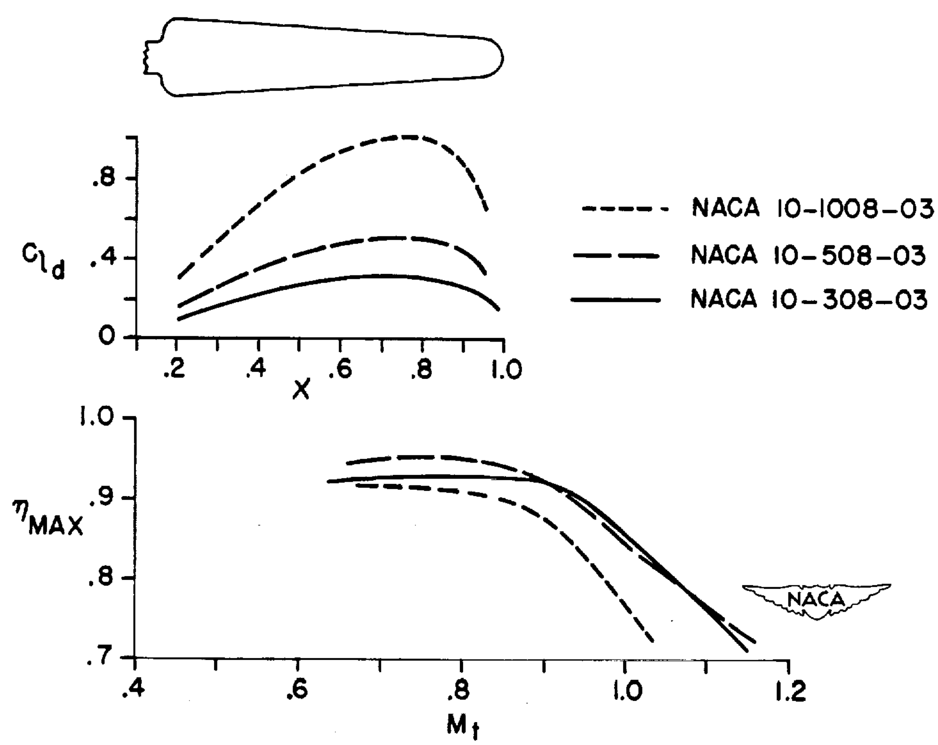


SECTION EFFICENCY OF TWO PROPELLER AIRFOILS

Figure 5.



EFFECT OF CAMBER ON PROPELLER CHARACTERISTICS

Figure 6.

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