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PROPELLER AEROACOUSTIC METHODOLOGIES*

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SUMMARY

This paper briefly covers aspects related to propeller performance by means of a review of propeller methodologies; presentation of preliminary wind tunnel propeller performance data taken in the NASA Lewis Research Center 10 x 10 wind tunnel; discussion of the predominent limitations of existing propeller performance methodologies; and a brief review of airfoil developments appropriate for propeller applications. This paper is intended as a status report with the complete study to be documented at a later date.

INTRODUCTION

Because of the increased emphasis on fuel efficiency for general aviation aircraft, there has been a renewed interest in the use of propellers. It has been estimated that in the use of the prop fan concept (Ref. 1), a fuel savings of approximately 36% can be realized over the turbofan through proper propeller design. Also, recent studies have shown a 5 to 7% savings in fuel efficiency can be obtained (Ref. 2) through proper propeller design and critical examinations of propeller-nacelle interactions. As a result, a study supported by the National Aeronautics and Space Administration Lewis Research Center was initiated involving the Ohio State University, Borst and Associates, Hartzell Propeller, Inc., and Rockwell Corporation of Bethany, Oklahoma to evaluate and enhance current analytical prediction methods for propellers designed specifically for the twin engine Rockwell Aerocommander 690B. This three year study has and will involve computer prediction studies in the theoretical evaluation of propeller performance; wind tunnel model tests conducted at the NASA Lewis Research Center; flight test comparisons; and enhancement of the theoretical methods by means of comparison with wind tunnel and flight tests. The intent of this paper is to briefly cover aspects related to propeller performance and to illustrate preliminary data resulting from the wind tunnel tests of two propellers in this study. It is intended that a report will be made available on the comparisons between the theoretical predictions and the complete experimental data set resulting from the wind tunnel tests.

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PROPELLER PERFORMANCE METHODS

A brief review of the methodologies (Ref. 3) used in predicting propeller performance (Fig. 1) has been included in this work for completeness. Propeller theories have proceeded from the simple Rankine-Froude momentum disc theory (Refs. 4,5) which assumes that the propeller disc is replaced by a disc with an infinite number of blades producing a uniform change in velocity of the stream passing through the disc. This theory is useful in calculating theoretical maximum efficiencies but does not deal in the details of the propeller configuration such as number of blades and blade thickness. These factors are considered in the blade element analysis (Refs. 6,7) the next degree of sophistication, which deals in the forward and rotational velocity components to determine the resultant velocity or the effective pitch angle and hence the angle-of-attack as seen by each airfoil section making up the propeller blade. Here the angle-of-attack is taken as the difference between the geometric pitch angle and the effective pitch angle (Fig. 2) and assumes that the induced flow past the blade element is the same as past a wing with an aspect ratio of six. The simple blade element theory has been used for preliminary calculations and in some cases gives accurate answers within 10% of the measured thrust and torque values.

More precise results may be obtained in the prediction of thrust and torque by calculating the local induced velocities at each radial station (Fig. 2) by means of vortex theory (Ref. 8). Here, the combination of simple momentum theory and blade element analysis results in a theory that also accounts for rotation of the slip stream. However this approach, although providing an accurate approximation, still does not account for tip losses, blade to blade interference, and nonuniform flow in the disc plane resulting from the presence of a nacelle.

The next order of development and accuracy came with the Goldstein lifting-line model (Ref. 9) where the blade is replaced by a series of horseshoe vortices as shown in Figure 1. The approximation of blade replacement by vortices is acceptable since most general aviation propellers have a relatively high aspect ratio. Also, the lifting line approach can utilize corrections for viscosity and compressibility but is accepted as an "approximate method" using the Goldstein factor. The Goldstein factor method is usually taken for lightly loaded propellers where the Betz condition holds, and does not apply to other than constant pitch propellers in uniform flow (Ref. 3). The lifting line problem can also be solved by the "rigorous method" using Lerb's induction factor method (Ref. 9) which is based on the velocity potential of helical vortex lines applied to any moderately loaded optimum or non-optimum propeller operating in a uniform or nonuniform free stream (Ref. 3). This is the method of analysis that has been used in the performance comparisons to be shown in a later section of this paper.

As the propeller configurations change to relatively small apsect ratio and/or large surface areas (Fig. 1) as in the prop-fan concept (Ref. 1), advanced analytical methods must be used such as the Ludwig-Ginzel lifting surface model (Ref. 10) to model the propeller flow field accurately. These advanced methods and the current state-of-the-art have been discussed by Bober and Mitchell (Ref. 11) in addition to the importance of wake modeling.

It is the purpose of the present effort to compare directly with experimental data the theoretical prediction results of vortex theory and lifting line theory to determine the ranges of applicability and levels of accuracy. The current wind tunnel tests cover a broad range in advance ratios, blade angle settings, and flight conditions for four general aviation propellers, each having different activity factors and propeller blade sections. In so doing, the current methods may be enhanced to provide increased accuracy in the prediction of propeller performance.

PROPELLER AIRFOIL DEVELOPMENT

Airfoil development for propeller applications has been limited with the continual use of the Clark Y and RAF 6 series airfoils. The last major development in this area occurred with the development of the NACA 16 series airfoils (Ref. 12) and as shown in Figure 3 does have relatively good performance in terms of the metric C_L/C_D as a function of C_L. This airfoil has the characteristic "flat bottom", maximum thickness occurring at approximately the 50% point, and a small leading edge radius with many of the design characteristics dictated by manufacturing constraints. Therefore many propellers of today incorporate the Clark Y or RAF 6 airfoil series during the initial 50% of the blade transitioning to the NACA 16 series which has a high drag divergence Mach number in the outer segment of the propeller where the resultant Mach numbers can approach unity.

Bocci (Ref. 13) in a paper published in 1977 described a new series of propeller airfoil sections entitled the ARA-D series. Here, the manufacturing constraints have been relaxed as shown in Figure 3 resulting in a section incorporating increased camber on the underside of the airfoil; drooped leading edge to prevent leading edge stall at high angle-of-attack; and an increased leading edge radius. The results of this design approach can be seen in Figure 3 with an improvement over the performance of the NACA 16 series at the high lift coefficients. The importance of the airfoil section to propeller performance is indicated in Figure 4 where it can be seen that the airfoil pressure distributions which evolve into the aerodynamic coefficients determine the load distribution and also allows an acoustic evaluation by the strip method. In a later study, the authors (Ref. 14) have compared the aerodynamic performance and acoustic estimates of the ARA-D, Clark Y and NACA 16 series airfoils.

In the discussions of propeller airfoil development, the wind tunnel tests of the propellers in this study incorporate a variety of airfoil sections, i.e.,

(a) Clark Y - NACA 16 airfoils
(b) ARA-D airfoils
(c) GA(W) airfoils
(d) 6 series airfoils

Since all have been designed for the Aerocommander 690 B, a comparison of the propeller performance can be interpreted as a comparison of these airfoils in terms of efficiency (η), thrust coefficient (C_T), and power coefficient (C_P) which are discussed in the following sections.

EXPERIMENTAL PROPELLER PERFORMANCE MEASUREMENTS

Propeller performance experimental values were obtained in the present program through use of the Propeller Test Rig (PTR) (Ref. 15) installed in the subsonic leg of the 10 foot x 10 foot supersonic wind tunnel located at the NASA Lewis Research Center. The configuration tested also incorporated equivalent body of revolution representating the actual nacelle of the Rockwell Aerocommander 690 B including a scaled representation of the spinner (Fig. 5). Pressure orifices were located along the periphy of the nacelle at two azimuthal locations to aid in evaluating the drag of the nacelle and its effect on the performance of the propeller.

Three flight conditions were examined for the approximately 0.5 scale propellers, i.e., take-off ($M = 0.11$), climb ($M = 0.23$), and the cruise condition ($M = 0.39$). The advance ratio (J) was varied for a fixed blade angle setting by fixing the test section Mach number through manipulation of the wind tunnel second throat and changing RPM. Values of propeller thrust and torque were deduced from the experimental measurements and the thrust coefficient (C_T), torque coefficient (C_Q), power coefficient (C_P), and efficiency (η) were determined by this method. An appropriate range in J values was examined with respect to the actual operating conditions or until stall-flutter was encountered.

The first propeller tested on the PTR in the configuration shown in Figure 5 consisted of Clark Y-NACA 16 airfoils with an activity factor of 101. The preliminary results are shown in Figure 6 for the cruise condition ($M = 0.39$, $\beta = 48^\circ$) in terms of efficiency (η) as a function of the advance ratio (J). Also shown in this figure are the theoretical estimates using vortex theory* and lifting line theory previously discussed. As can be seen, at the lower J values the lifting line prediction coincides with the experimental data with a resulting overprediction for J values in excess of 2.3. This may be compared directly with the vortex theory results which overpredicts the experimental data over the entire range of J values. A similar result is also found for an off-design condition as shown in Figure 7. Consideration of the climb condition ($M = 0.23$, $\beta = 32^\circ$) for this propeller, shown in Figure 8, indicates acceptable agreement between experiment and lifting line theory over the range in J values. Here vortex theory agrees well with the experimental data at the low J values with disagreement occurring at J values in excess of 1.2. As found previously, an investigation of the off-design condition as shown in Figure 9 also produces similar results.

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*The vortex theory is presently under examination to include the influence of the blade-spinner interference which could result in better correlation with experiment.

The second propeller tested having an activity factor of 83 utilized the ARA-D airfoil sections previously discussed. The initial comparisons are shown in Figure 10 and indicate that the lifting line prediction provides a reasonable correlation with experimental data for the cruise condition at a β of 48°. Here again, the vortex theory overpredicts that of the experimental data.

A complete set of data including comparisons with theory for C_T, C_Q, η, and C_P will be published for all four propellers tested. Determination of the range of validity of these theories in comparison with experimental data can then be investigated. Also, utilization of a wake rake probe (Fig. 11) is presently in use to obtain measurements of total pressure deficit, flow angularity, and static pressure measurements behind the disc plane of each propeller tested as a function of radial location. These data will result in independent thrust measurements as well as details of the propeller wake which can be compared directly to the current theoretical wake model being used. These results will be included in the reports previously mentioned at a later date.

LIMITATIONS OF CURRENT ANALYSES

The theoretical analyses that have been utilized in the comparisons with experimental data previously discussed are analytical models which contain limitations. For example, the importance of an accurate wake model and propeller/nacelle interactions has been emphasized by Bober (Ref. 11) in the prediction of high speed propeller performance predictions. Further, the result of a finite blade length, i.e., recognition of tip flow is necessary for an evaluation of three-dimensional effects. This effect has been treated by Cooper (Ref. 16) by obtaining a correction factor to the lift-curve slope as a function of the radial location but is valid for propellers using only NACA 16 and 6 series airfoils.

Also when considering limitations, the area of centrifugal viscous effects on the lift coefficient should be considered. In an experimental investigation by Himmelskamp (Ref. 17), he had found that there is a significant relationship between the magnitude of C_L and the radial location of the propeller blade. In a series of tests with a propeller made up of G0625 airfoils, Himmelskamp fixed the angle-of-attack at each radial location and measured the section lift coefficient. These values of C_L were then compared to the two-dimensional lift coefficient, as given in Figure 12, for the $\alpha = 5°$ case and found to be considerably higher with the greatest difference occuring at the root and decreasing as the propeller radius increased. These differences may be attributed to centrifugal viscous effects which obviously are not accounted for in two-dimensional theory. Since all propeller performance analyses utilize an airfoil data bank based upon two-dimensional experimental and analytical data, the differences indicated in Figure 12 if properly modeled could have a significant influence in the prediction accuracy of propeller performance theoretical values and resulting comparisons with experimental data.

As previously indicated, propeller performance analyses utilize airfoil data banks consisting of wind tunnel test and analytical computer codes.

Advancements made in the theoretical analysis of airfoils has been considerable with the availability of such subcritical computer codes as Smetana, et. al. (Ref 18) and Eppler (Ref. 19). The more extreme case of both subcritical and supercritical flow over an airfoil can also be treated analytically as given by Garabedian, et. al. (Ref. 20) and Carlson (Ref. 21). Also the results of massive separation on an airfoil, i.e., theoretical investigations of the airfoil maximum lift coefficient has been under study by Barnwell (Ref. 22), Carlson (Ref. 23), and Dvorak (Ref. 24) and are being used on a limited basis.

To illustrate the applicability of these codes and resulting limitations, the LS(1)-0413 airfoil theoretical and experimental (Ref. 25) pressure distribution is shown in Figure 13 for $M = 0.755$, $\alpha = 0^\circ$, and Reynolds number of 5.11×10^6 condition. The comparison between experiment and theory is reasonable on both the upper and lower surface of the airfoil with respect to the maximum negative and positive C_p magnitude, location of the shock wave, and the base pressure value. However, if the Mach number is increased to $M = 0.802$ for the same condition of α and Reynolds number as shown in Figure 14, the mismatch between theory and experiment is evident indicating deficiencies in the theoretical analyses and/or experiment.

PROPELLER ACOUSTIC ANALYSIS MODEL

The emphasis has been on the propulsion performance of general aviation propellers, however recent effort has resulted in the design of efficient as well as quiet propellers. To this end an acoustic analysis (Ref. 26) has been derived that, provided the pressure distributions at several radial locations along the blade are specified, the resulting total noise due to loading and thickness can be predicted. The characteristic acoustic pressure signatures are shown in Figure 15 for the near field condition, from which the sound pressure level (dB) as a function of harmonic number or multiples of the fundamental can be calculated (Fig. 16). The accuracy of this theoretical approach is shown in Figure 16, which shows the comparison between measured and predicted noise for a series of static tests conducted by Hubbard (Ref. 27) for two near field locations. As can be seen, the comparison is reasonable as found in several other applications (Ref. 28) of this theoretical approach.

It was intended in the current study to obtain near field acoustic measurements of the propellers tested (Fig. 17). However, there are a series of problems associated with tunnel wall conditions that are currently under study before acoustic data can be taken with the desired accuracy.

SUMMARY

A preliminary summary of the study to date has indicated that:

- lifting line analysis gives overall better agreement with experimental results;

- at design climb, lifting line agrees well with measurements but overpredicts cruise performance;
- vortex theory overpredicts experimental results at both climb and cruise conditions;
- present prediction methods require improvement.

It is intended that these wind tunnel data be compared to full scale flight test during 1980. Also, enhancement of the present theoretical models will be required as indicated in this phase of the study resulting in better comparison between experimental data and analytical predictions.

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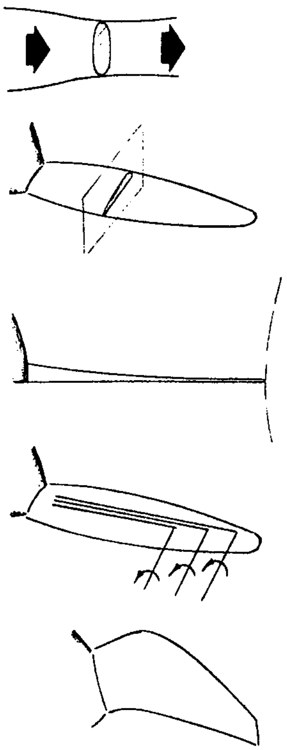
PROPELLER PERFORMANCE METHODS - REVIEW

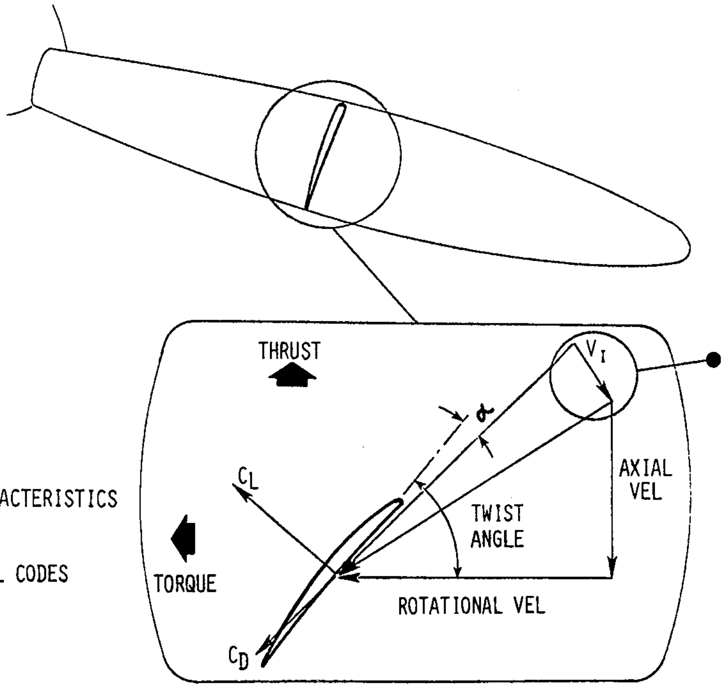


- MOMENTUM DISC THEORY
- BLADE ELEMENT ANALYSIS
- VORTEX THEORY
- LIFTING LINE THEORY
- ADVANCED ANALYTICAL METHODS

Figure 1

CURRENT PERFORMANCE METHODS

- AIRFOIL CHARACTERISTICS
  - TEST
  - ANALYTICAL CODES
  - DATA BANK



- INDUCED VELOCITY
  - VORTEX THEORY
  - LIFTING LINE

Figure 2

AIRFOIL PERFORMANCE COMPARISON

(M = 0.4 T/C = 10%)

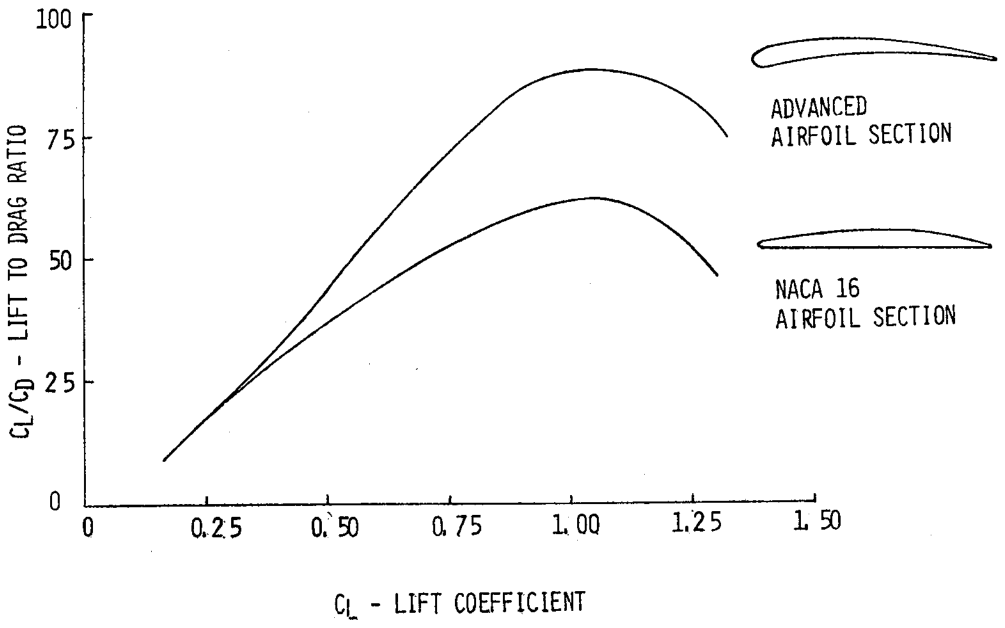
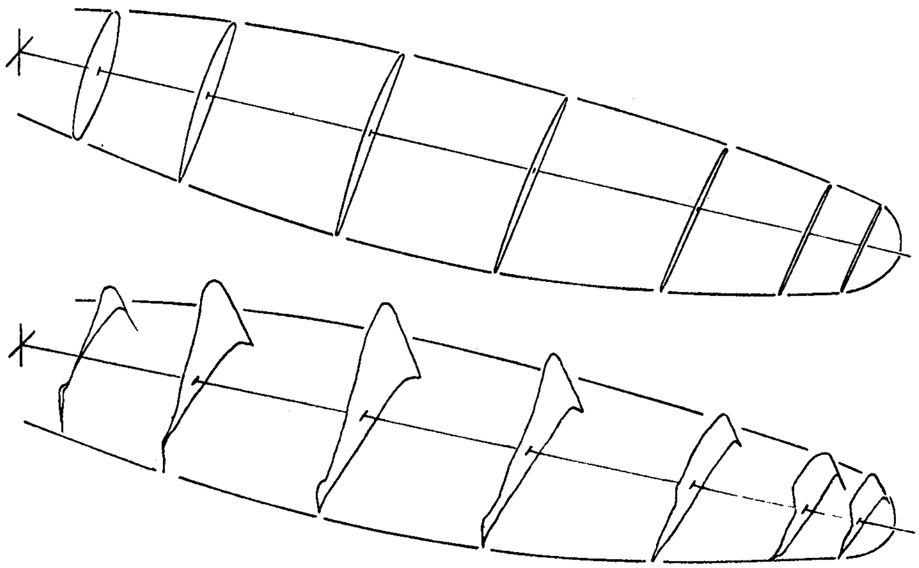


Figure 3

BLADE AIRFOIL ANALYSIS



● PRESSURE DISTRIBUTIONS { - SECTION AERODYNAMIC PROPERTIES
- ACOUSTIC PRESSURE SIGNATURE

Figure 4

GENERAL AVIATION WIND TUNNEL MODEL

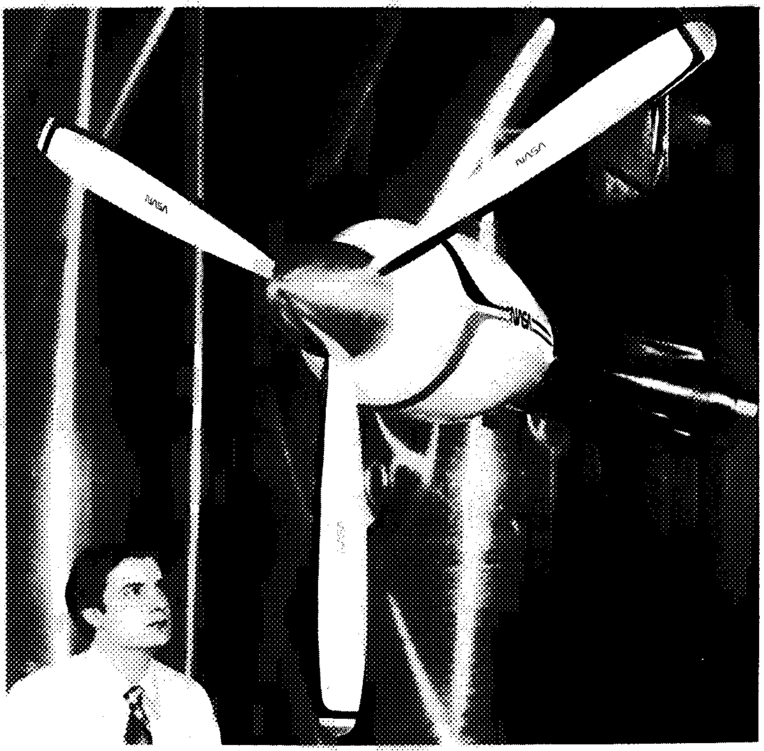


Figure 5

CRUISE PERFORMANCE COMPARISON

M = 0.39/ AF = 101/ CLARK Y - NACA 16 AIRFOILS

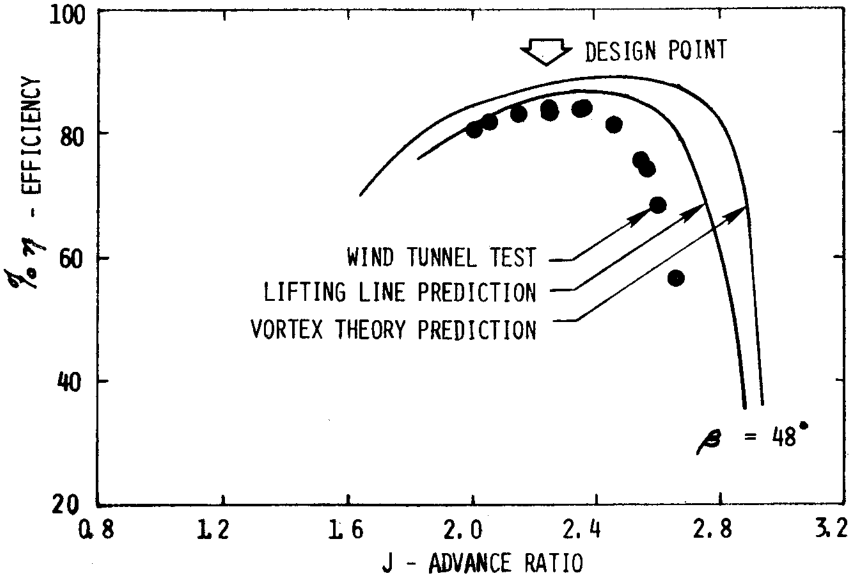


Figure 6

OFF-DESIGN CRUISE PERFORMANCE COMPARISON
M = 0.39/ AF = 101/ CLARK Y - NACA 16 AIRFOILS

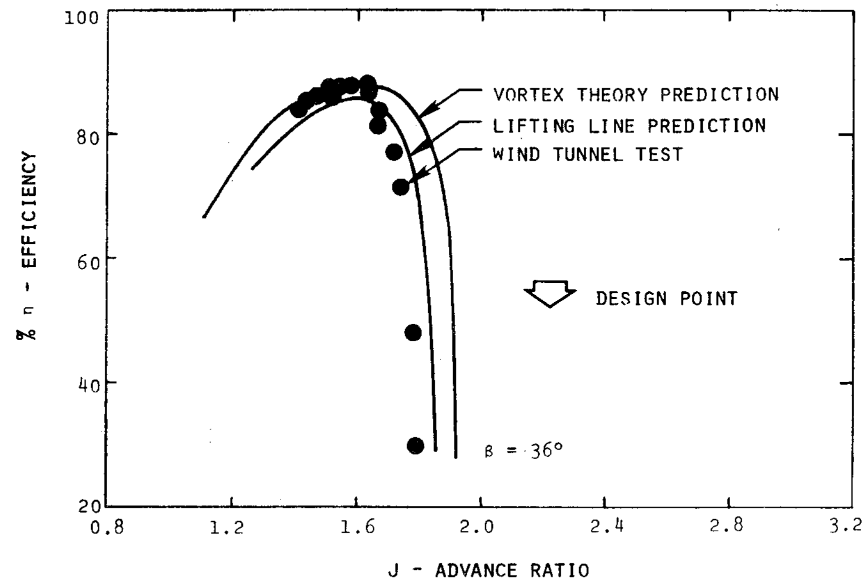


Figure 7

CLIMB PERFORMANCE COMPARISON
M = 0.23/ AF = 101/ CLARK Y - NACA 16 AIRFOILS

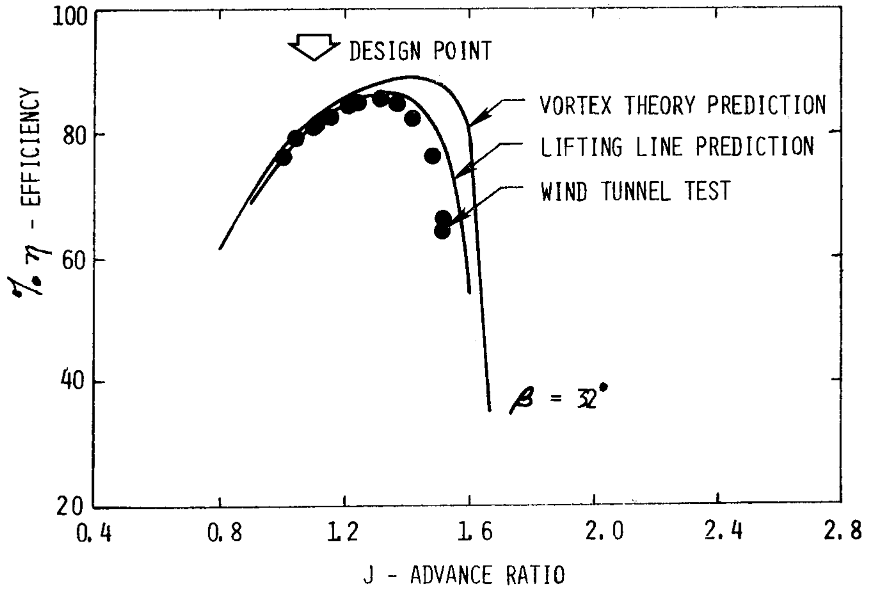
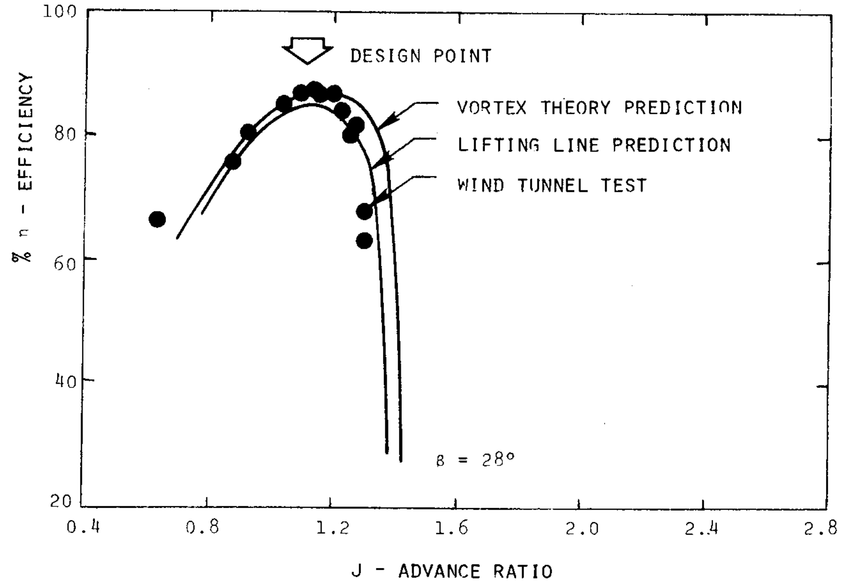


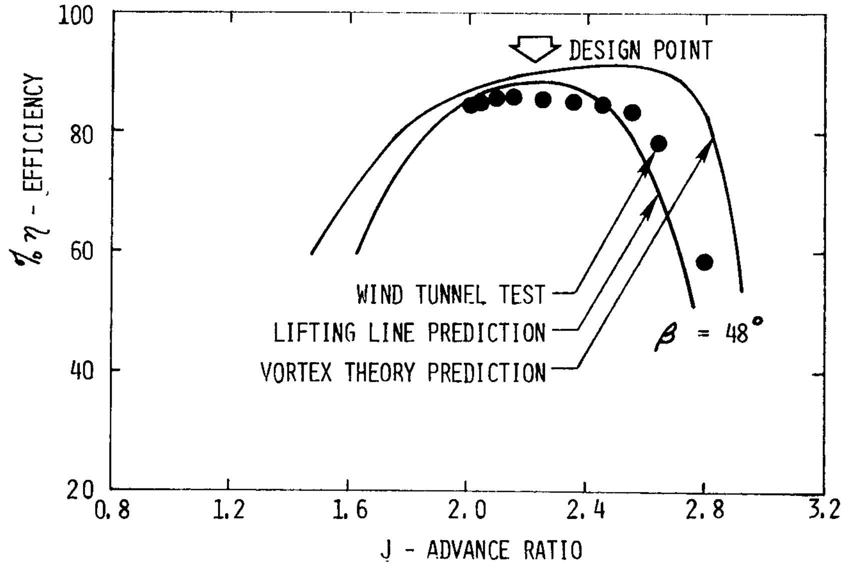
Figure 8



OFF-DESIGN CLIMB PERFORMANCE COMPARISON

M = 0.23/ AF = 101/ CLARK Y - NACA 16 AIRFOILS

Figure 9



CRUISE PERFORMANCE COMPARISON

M = 0.39/ AF = 83/ ARA-D AIRFOILS

Figure 10

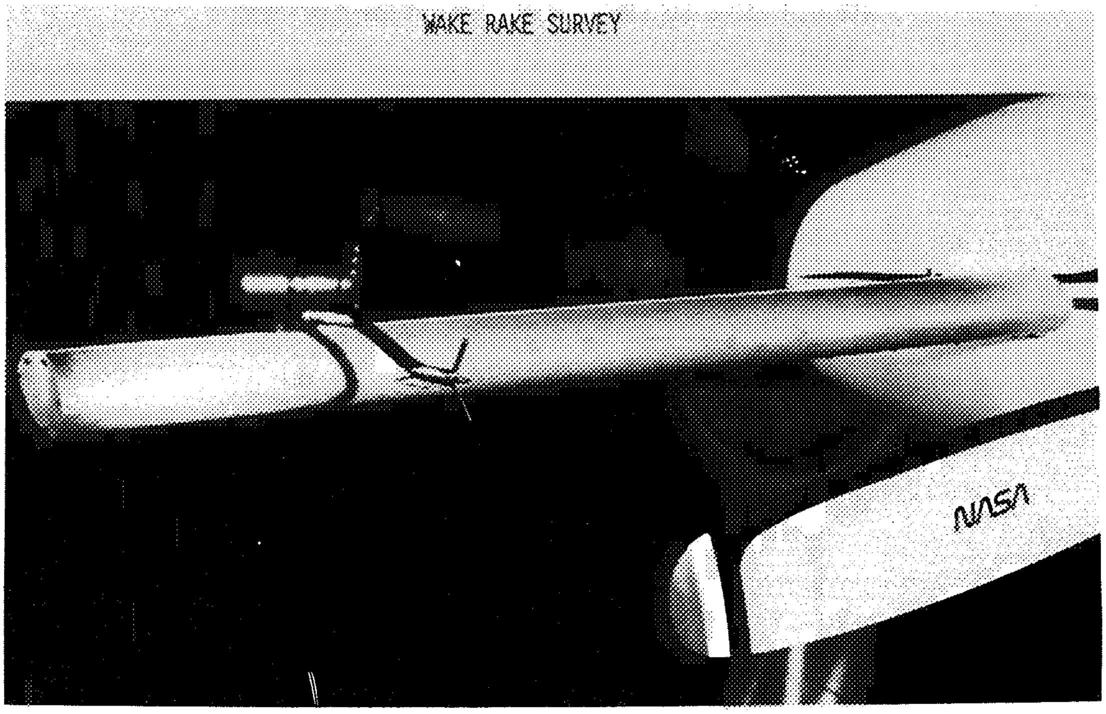

WAKE RAKE SURVEY

Figure 11

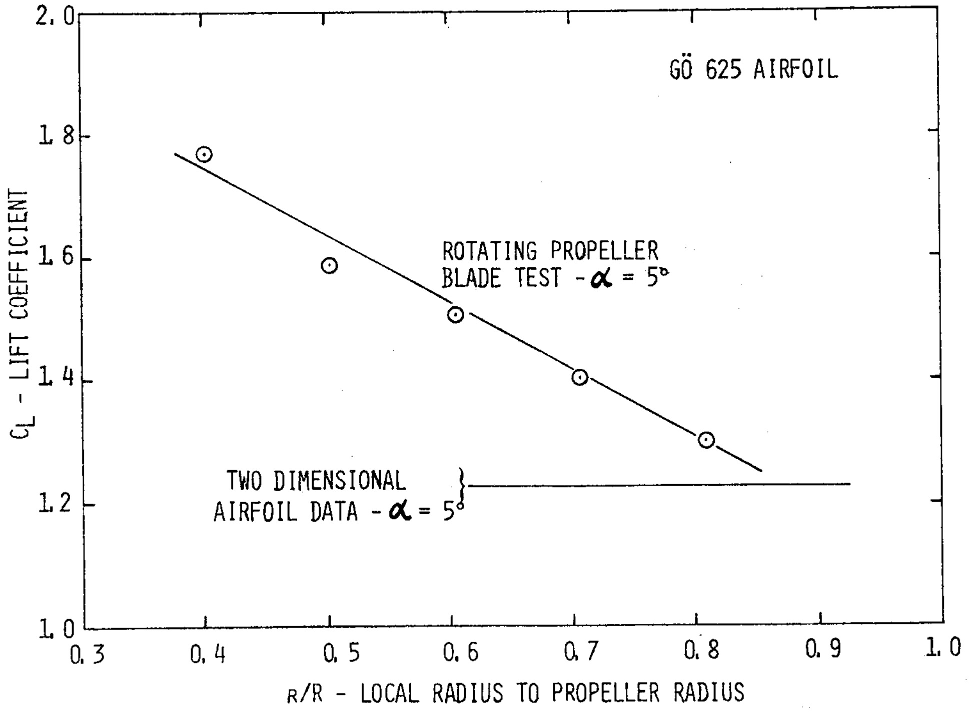

CENTRIFUGAL VISCOUS EFFECTS ON LIFT

Figure 12

AIRFOIL PRESSURE DISTRIBUTION COMPARISON - THEORY/EXPERIMENT

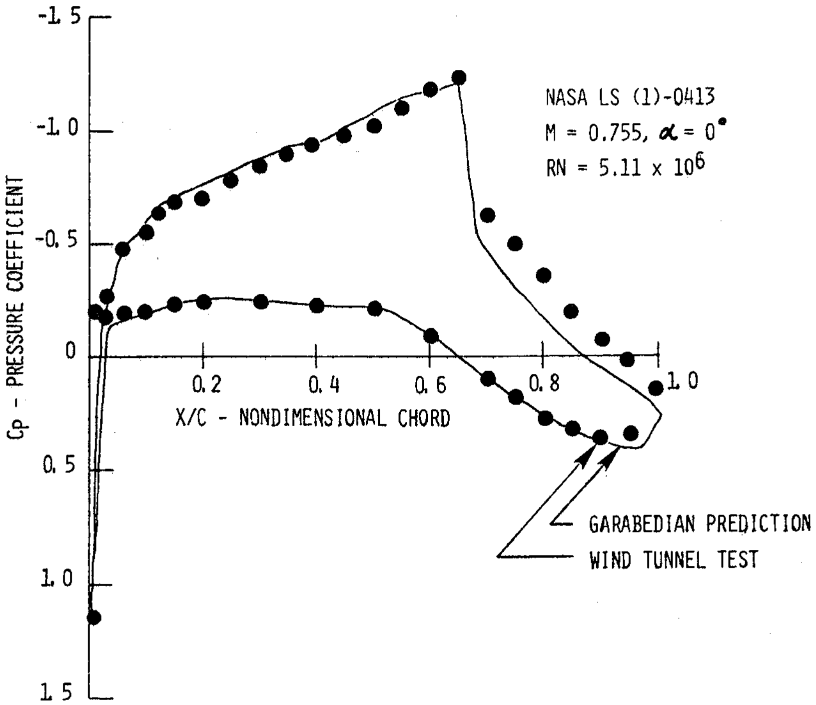


Figure 13

AIRFOIL PRESSURE DISTRIBUTION COMPARISON - THEORY/EXPERIMENT

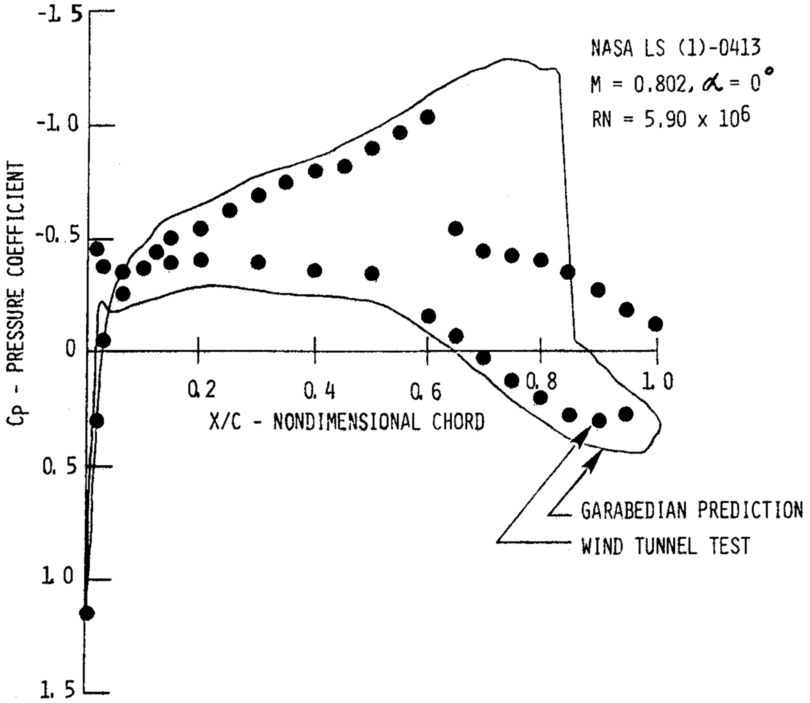


Figure 14

ACOUSTIC ANALYSIS MODEL

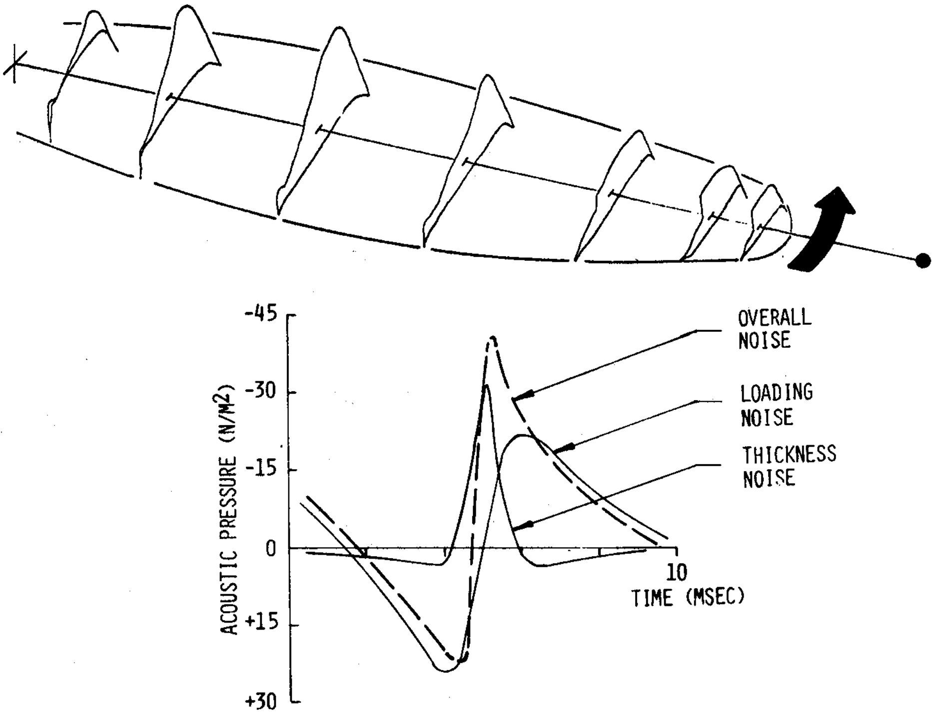


Figure 15

COMPARISON OF MEASURED AND PREDICTED NOISE

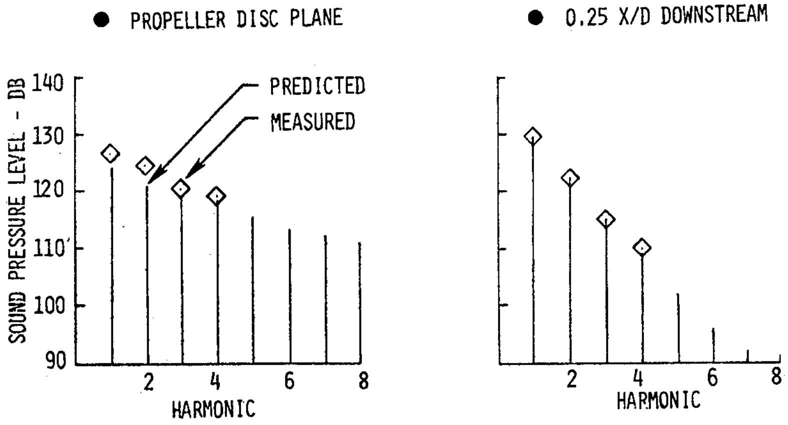


Figure 16

NEAR FIELD ACOUSTIC MEASUREMENTS

Figure 17