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Summary

Many current comprehensive rotorcraft analyses employ lifting-line methods that require main rotor blade airfoil data, typically obtained from wind tunnel tests. In order to effectively evaluate these lifting-line methods, it is of the utmost importance to ensure that the airfoil section data are free of inaccuracies. A critical assessment of the SC1095 and SC1094R8 airfoil data used on the UH-60 main rotor blade was performed for that reason. Nine sources of wind tunnel data were examined, all of which contain SC1095 data and four of which also contain SC1094R8 data. Findings indicate that the most accurate data were generated in 1982 at the 11-Foot Wind Tunnel Facility at NASA Ames Research Center and in 1985 at the 6-inch-by-22-inch transonic wind tunnel facility at Ohio State University. It has not been determined if data from these two sources are sufficiently accurate for their use in comprehensive rotorcraft analytical models of the UH-60. It is recommended that new airfoil tables be created for both airfoils using the existing data. Additional wind tunnel experimentation is also recommended to provide high quality data for correlation with these new airfoil tables.

Symbols

a	correlation parameter for C_{d_0} at low supersonic speeds
b	wind tunnel model span, ft
c	wind tunnel model chord, ft
C_d	section drag coefficient
C_{d_0}	section drag coefficient at zero lift
c_f	mean skin friction coefficient
C_l	section lift coefficient
$C_{l_{max}}$	maximum section lift coefficient
C_{l_α}	$\partial C_l/\partial\alpha$ = average section lift curve slope at zero lift
$C_{l_{\alpha_{max}}}$	maximum value of C_{l_α} at $M < 1.0$
$C_{l_{\alpha_{min}}}$	minimum value of C_{l_α} at $M < 1.0$
$C_{l_{\alpha_{recovered}}}$	recovered value of C_{l_α} at $1.0 > M > 1.1$
C_s/c_F	form drag/friction drag
h	wind tunnel test section height, ft
K	correlation parameter for airfoil section drag due to lift
L_p/c	airfoil perimeter/chord
$(L/D)_{max}$	maximum lift-to-drag ratio
L	lift, lb
M	Mach number
M_1	Mach number at which the slope of C_{l_α} changes from "+" to "–"
M_{DD}	drag divergence Mach number
P_{error}	measured pressure transducer steady bias error, psia
P_l	lower surface pressure, psia
P_u	upper surface pressure, psia
t/c	thickness-to-chord ratio
S_A	mean value of airfoil pressure coefficient
R_c	free-stream Reynolds number
R_{N_0}	Reynolds number in drag correlation
V	free-stream velocity, ft/s
α	angle of attack, deg or rad
α_{ZL}	zero-lift angle of attack, deg or rad
β	$\sqrt{1 - M^2}$
μ	$1/\beta$
$\partial C_{l_\alpha}/\partial M$	C_{l_α} gradient at speeds greater than M_1
$\partial C_{d_0}/\partial M$	C_{d_0} gradient at speeds greater than M_{DD}
γ	ratio of specific heats, 1.4 for air
ρ	density, slugs/ft^3

Introduction

NASA, in cooperation with the U.S. Army Aviation and Troop Command (ATCOM), is engaged in a program to provide and validate the technology and methodology required to improve the performance, dynamics, acoustics, handling qualities, and cost of civil and military rotorcraft. A major element of this program, the UH-60 Phase II Airloads Program, consists of ground based and flight research of the UH-60 Blackhawk helicopter with a pressure instrumented blade and a full suite of other instrumentation.

NASA and ATCOM are currently preparing for rigorous analysis methodology validation using high quality data generated from the UH-60 Phase II Airloads Program. Analysis methodology validation involves assessing and improving state-of-the-art comprehensive analytical models through exhaustive correlative studies in performance, dynamics, and rotor structural loads and airloads. In order to assess and improve the theories and assumptions employed in comprehensive analytical models, accurate vehicle representations must be established.

The main rotor blade airfoil section characteristics are among the most important parts of the vehicle representation. The airfoil sections on the UH-60 Blackhawk helicopter are the SC1095 and SC1094R8 utilized on the main rotor blade shown in figure 1. The profiles of these airfoils are shown in figure 2.

Sikorsky Aircraft, a Division of United Technologies Corporation, was tasked to provide NASA with all known steady, 2-D wind tunnel data on the SC1095 and SC1094R8 airfoils. Nine data sets (refs. 1–9) were identified and provided to NASA, all of which contained SC1095 data and four of which contained SC1094R8 data. This report documents an assessment of that data for both airfoils.

An effort similar to the UH-60 Phase II Airloads Program was performed on an H-34 helicopter by Scheiman in the early 1960s. That experiment has long been a standard for rotor airloads data, but it did not include high speeds. Furthermore, rotor systems have evolved dramatically from the early 1960s. The UH-60 Phase II Airloads Program will consider high speeds and will gather data at much higher sample rates. The U.S. rotorcraft industry has played a key role in defining the requirements for this program to ensure it meets their needs. Also, a formal recommendation resulting from a peer review of the program in 1990 was a primary motivator for the work presented in this report.

I would like to acknowledge and thank Mr. Robert Flemming from Sikorsky for his thorough review of the data and for his comments, all of which have been incorporated in this report.

Description of Data

Nine sets of UH-60 airfoil data have been considered. The sources of these data sets which contain SC1095 and SC1094R8 airfoil data are listed in table 1. These data sets are identified in table 1 and throughout this report, as Experiment 1, Experiment 2, and so on, through Experiment 9. Pertinent information about the experiments, the wind tunnel facilities, airfoils, and measurement devices are also noted in this table. Some details of these experiments are discussed in this section.

The primary objectives of three of the experiments were to assess current technology airfoils, either stand-alone or compared with prototypes. Experiments 3 and 8 gathered steady, 2-D data on the SC1095 and SC1094R8 airfoils and compared them to prototype airfoils. Experiment 7 gathered SC1095 data for correlation with a computational fluid dynamics code.

Evaluation of Experiment 7 data revealed gross discrepancies relative to the data from all the other experiments. The published report documenting this experiment noted that inaccurate tunnel wall corrections were applied to generate the reported data (ref. 7). Regrettably, appropriate wall corrections are not available and the tunnel configuration has since been permanently modified.

Some experiments examined alternate methods of testing. For example, the primary objective of Experiment 2 was the testing of a Tunnel Spanning Wing Apparatus (TSW or TSA) which fit inside a wind tunnel test section. The TSW was evaluated in Experiments 2 and 5, and later used in Experiment 8. Experiment 2 attributed pre-stall "bumps" in lift coefficient at high angles of attack to model flexibility. Experiment 5 gathered data with and without a center span device that alleviated the model flexibility problems noted in Experiment 2. Experiment 5 published two sets of SC1095 wake drag data, identified as 5a and 5b. The 5a drag data accounted for the difference in static pressures on each side of the wake behind the airfoil, whereas the 5b drag data did not.

The remaining four experiments were primarily concerned with the study of trends. Experiment 1 considered the influence of various surface irregularities relative to a baseline SC1095 airfoil. Experiment 4 studied icing conditions relative to baseline SC1095 and SC1094R8 airfoil characteristics. This experiment generated relatively small amounts of data under normal, non-icing conditions. Data published from two alternate lift measurement approaches devised in Experiment 4 were also evaluated. Experiment 6 studied the effect of Reynolds number on both the SC1095 and the SC1094R8 airfoils. This experiment documented known problems in determining $C_{l_{max}}$, and the airfoils used in that experiment were tabbed. The tabs were deflected upward approximately 3 degrees. The tabs also changed the thickness-to-chord ratios to 0.091 and 0.09 for the SC1095 and SC1094R8 airfoils, respectively. Untabbed thickness-to-chord ratios are 0.095 and 0.094 for the SC1095 and SC1094R8, respectively. Finally, Experiment 9 measured the effects of dynamic stall relative to baseline SC1095 steady, 2-D characteristics. Data from Experiment 9 were limited to speeds less than M = 0.3.

In summary, although all of the data from these nine experiments were examined, Experiment 7 and some Experiment 4 results were not published in this report. Experiment 7 results were omitted because of the aforementioned problem with the tunnel wall corrections. Experiment 4 data gathered using the two alternate lift measurement approaches were also omitted because no attempt was made to address known anomalies noted at certain test conditions. In each instance the experimenter was consulted prior to omitting the results, and concurrence was obtained.

Evaluation Methodology

The methodology developed by McCroskey (ref. 10) and first applied to NACA 0012 data was used to evaluate the SC1095 and SC1094R8 data. This methodology uses specific criteria to separate accurate data from inaccurate data. All the data are then placed into one of four groups that further reflect varying levels of accuracy. A short summary of the aforementioned criteria, and the definitions of the four groups are given in this section.

Criteria

Generally speaking, for $M < 0.6$ and between $10^6 < R_c < 10^7$, accurate data is distinguished from inaccurate data if they exhibit the following characteristics:

1. 0.10 per degree $< \beta C_{l_\alpha} < 2\pi$ per radian, where $b = \sqrt{1 - M^2}$, 0.10 is a known boundary, and 2π is the theoretical lift-curve slope.
2. βC_{l_α} and βC_{d_0} are independent of Mach number.
3. βC_{l_α} and βC_{d_0} are slightly dependent on Reynolds number.

Groups

Four groups were defined by McCroskey to distinguish varying levels of accuracy. A graphical approach is used to place the data into each of these groups. This approach begins with two plots; βC_{l_α} versus R_e and C_{d_0} versus R_e for data less than M = 0.6 and between $10^6 < R_c < 10^7$. Group 1 quality data should have values for both βC_{l_α} and C_{d_0} within ±0.0005 and ±0.0002, respectively, of a log curve fit approximation of only the accurate data identified by the aforementioned criteria. Group 1 quality data are of sufficient accuracy for use in comprehensive analytical input models. This is further examined in the Discussion section.

Group 2 quality data should have values for both βC_{l_α} and C_{d_0} within ±0.004 and ±0.001, respectively, of the log curve fit of only the accurate data identified by the aforementioned criteria. It has not been determined whether Group 2 data are sufficiently accurate for use in comprehensive analytical models. This will also be examined in the discussion section.

Group 3 quality data should have values for either βC_{l_α} *or* C_{d_0} within the Group 2 tolerances. Finally, Group 4 quality data have values for both βC_{l_α} and C_{d_0} outside the Group 2 tolerances.

Once the groups have been established, C_{l_α} C_{d_0}, and $(L/D)_{max}$ are examined throughout the full range of Mach numbers. The trends that these parameters exhibit as a function of Mach number are characterized by their inflection points, or the points at which the trends abruptly change direction. The inflection points of interest are:

1. C_{l_α}: $C_{l_{\alpha_{max}}}$, $C_{l_{\alpha_{min}}}$, and $C_{l_{\alpha_{recovered}}}$
2. C_{d_0}: M_{DD} and $C_{d_{0_{max}}}$
3. $(L/D)_{max}$: maximum value of $(L/D)_{max}$
4. $C_{l_{max}}$: maximum value of $C_{l_{max}}$

The accuracy with which these inflection points can be estimated, in addition to the continuous and unscattered behavior of the data between the inflection points, are indications of data consistency.

It is important to realize that the groups are defined at low speeds for a given range of Reynolds number. This does not ensure that the data in any given group will retain the same accuracy at higher speeds. It is therefore important to plot all groups throughout the full range of Mach numbers and check the consistency of the data both within the individual groups and among the groups themselves.

Results

The methodology described in the previous section was applied to the data from the experiments for both airfoils. The results of the evaluation of the data are presented in this section. Table 2 lists pertinent information about the wind tunnel facilities used in all nine experiments, tunnel wall corrections, and known accuracies of experiments that generated the NACA 0012 data previously evaluated by McCroskey.

SC1095 Airfoil

Evaluation of βC_{l_α}– Figure 3 shows derived βC_{l_α} values from the experiments plotted versus $\log(R_e)$. Figure 4 shows a log curve fit of the data only between $0.10 < \beta C_{l_\alpha} < 2\pi$, along with Group 1 and Group 2 tolerances. Balance data from Experiment 2 and pressure data from Experiments 3 and 6 values are within the Group 2 tolerance; however, none of the experiments are consistently within the Group 1 tolerance. The implication is that Experiments 2 (balance), 3, and 6 produced Group 2 quality lift coefficient data because the derived βC_{l_α} values are within the Group 2 tolerance.

Evaluation of C_{d_0}– Figure 5 shows C_{d_0} values from the experiments plotted versus $\log(R_e)$, along with a log curve fit of that data, and Group 1 and Group 2 tolerances. Wake drag data from Experiments 1, 4, 5a, 6, and 8 appear to be within or very near the Group 1 tolerances. Wake drag data from Experiments 2, 3, 5b, and 9 are all within the Group 2 tolerances. The implication is that all of the experiments produced Group 2 quality drag coefficient data because the C_{d_0} values are within the Group 2 tolerance.

Groupings– Based entirely on the above evaluations of βC_{l_α} and C_{d_0} as presented in figures 3 through 5 the groupings for the SC1095 data are:

Group 1	None
Group 2	Experiments 2 (balance and wake drag), 3, and 6
Group 3	Experiment 1, 2 (pressure), 4, 5, 8, and 9
Group 4	None

Results for C_{l_α}– The variation of C_{l_α} throughout the full range of Mach numbers is shown in figure 6, with each group duly noted. An examination of the Group 2 data reveals that there is a smooth and consistent trend in the variation of C_{l_α} with Mach number up to $M = 0.84$. This trend is noticeably different than that exhibited by the Group 3 data, and less scattered than the Group 3 data as well. A maximum value of C_{l_α} occurs at $M = 0.84$ and a minimum value occurs at $M = 0.90$, with a small recovery at speeds greater than $M = 0.95$. Maximum, minimum, and recovered values of C_{l_α} can be roughly estimated from the data shown in figure 6. The McCroskey-Smith expression superimposed on figure 6 will be discussed in the next section.

In summary, no lift coefficient data exist beyond $M = 1.10$, the best lift coefficient data available are found to be Group 2 quality, and that the data are only consistent at speeds up to $M = 0.84$.

Results for C_{d_0}– The variation of C_{d_0} throughout the full range of Mach numbers is shown in figure 7, with each group duly noted. There is a consistent trend in the variation of the Group 2 C_{d_0} with Mach number up to $M = 0.80$. Experiment 8 balance data appear to be higher than the established trend beyond $M = 0.70$. A maximum value of C_{d_0} can be roughly estimated at $M = 0.98$. The McCroskey-Smith expression superimposed on figure 7 will be discussed in the next section.

In summary, no drag coefficient data exist beyond $M = 1.10$, the best drag coefficient data available are found to be Group 2 quality, and the data are only consistent at speeds up to $M = 0.80$.

Results for $(L/D)_{max}$ and $C_{l_{max}}$– Figures 8 and 9 show that $(L/D)_{max}$ and $C_{l_{max}}$ data from Experiments 2 (balance and wake drag), 3, and 6 are consistent at speeds between $0.50 < M < 0.84$. However, scatter below $M = 0.5$ is evident. McCroskey showed that good data tend to exhibit high $(L/D)_{max}$ and $C_{l_{max}}$ values at low speeds. $(L/D)_{max}$ and $C_{l_{max}}$ data from Experiment 3 data were noticeably higher at low speeds than the other experiments that produced Group 2 quality data. Based on these figures, it appears that $(L/D)_{max}$ and $C_{l_{max}}$ occur at roughly $M = 0.3$.

The inflection points of interest for C_{l_α}, C_{d_o}, $(L/D)_{max}$, and $C_{l_{max}}$ for the SC1095 airfoil data are given in table 3.

SC1094R8 Airfoil

Evaluation of βC_{l_α}– Figure 10 shows derived βC_{l_α} values from the experiments plotted versus $\log(R_e)$. Figure 11 shows a log curve fit of the data within $0.10 < \beta C_{l_\alpha} < 2\pi$, along with Group 1 and Group 2 tolerances. Some of the data from each experiment are outside the Group 2 tolerances. At least half of the balance data from Experiment 8 and half of the pressure data from Experiments 3, 4, and 6 are scattered within the Group 2 tolerances. None of the experiments are consistently within the Group 1 tolerances. It can be concluded that all of these experiments produced a certain amount of Group 2 quality lift coefficient data because the derived βC_{l_α} values are within the Group 2 tolerance.

Evaluation of C_{d_o}– Figure 12 shows C_{d_o} values from all the experiments plotted versus $\log(R_e)$, along with a log curve fit of that data, and Group 1 and Group 2 tolerances. Most or all of the data from Experiments 3, 6, and 8 are within the Group 2 tolerances. Data from Experiment 8 are scattered, with a few points outside the Group 2 tolerance boundary on the high side. Data from Experiment 4 were not used in deriving the log curve fit and are outside of the Group 2 tolerance. The implication is that Experiments 3, 6, and 8 produced a certain amount of Group 2 quality drag coefficient data because the C_{d_o} values are within the Group 2 tolerance.

Groupings– Based entirely on the evaluation of βC_{l_α} and C_{d_o} as presented in Figures 10 through 12 the groupings for the SC1094R8 data are

Group 1	None
Group 2	Experiments 3, 6, and 8
Group 3	Experiment 4
Group 4	None

Results for C_{l_α}– The variation of C_{l_α} throughout the full range of Mach numbers is shown in figure 13. An examination of the Group 2 data reveals that there are slightly conflicting trends in the variation of C_{l_α} with Mach number. Experiment 6 values tend to be higher than the trend established by the other experiments below M = 0.60. A maximum value occurs at M = 0.83, but no minimum or recovered values can be established. The data tend to be more scattered beyond M = 0.70 than at lower speeds, regardless of the groupings. The Smith expression superimposed on figure 13 will be discussed in the next section.

In summary, no lift coefficient data exist beyond M = 0.90, the best lift coefficient data available are Group 2 quality, and these data are only consistent at speeds up to M = 0.70.

Results for C_{d_o}– The variation of C_{d_o} throughout the full range of Mach numbers is shown in figure 14. There are conflicting trends in the variation of C_{d_o} with Mach number beyond M = 0.70. Wake data from Experiment 6, and to a lesser extent from Experiments 3 and 8, exhibit lower drag values than the balance data from Experiment 8. Figure 14 also shows that some Experiment 8 wake drag data are high at low speeds, and those data points correspond to the high drag values noted in figure 12. A maximum value of C_{d_o} cannot be determined. The Smith expression superimposed on figure 14 will be discussed in the next section.

In summary, no drag coefficient data exist beyond M = 0.90, the best drag coefficient data available are Group 2 quality, and the data are only consistent at speeds up to M = 0.70.

Results for $(L/D)_{max}$ and $C_{l_{max}}$– Figures 15 and 16 show $(L/D)_{max}$ and $C_{l_{max}}$ data, respectively, from all the experiments. These data are only consistent at speeds between $0.60 < M < 0.84$. Scatter below M = 0.6 is evident. Experiment 6 again appears to exhibit a different $(L/D)_{max}$ and $C_{l_{max}}$ trend than the other experiments, which all tend to be in better agreement. Experiments 3 and 8 exhibit slightly higher values of $(L/D)_{max}$ and $C_{l_{max}}$. Based on these figures it appears that $(L/D)_{max}$ and $C_{l_{max}}$ occur at roughly M = 0.3.

The inflection points of interest for C_{l_α}, C_{d_o}, $(L/D)_{max}$, and $C_{l_{max}}$ for the SC1094R8 airfoil data are given in table 3.

The results of this evaluation show that none of the experiments produced Group 1 quality data. Some of the experiments produced Group 2 quality data. Experiment 3 produced Group 2 quality data for both the SC1095 and the SC1094R8 airfoils. Experiment 8 produced Group 2 quality data for the SC1094R8 airfoil. The SC1095 data was found to be consistent up to M = 0.84 for lift coefficient and M = 0.80 for drag coefficient. The SC1094R8 data was found to be consistent up to M = 0.70 for both lift and drag coefficient, except for some scattered drag data at low speeds. Other experiments that produced Group 2 quality data were found to exhibit slightly different trends, inconsistencies, or lower values of $(L/D)_{max}$ and $C_{l_{max}}$ relative to the aforementioned experiments.

During the initial phases of this evaluation, the experimenters responsible for the publication of the SC1095 and SC1094R8 data were contacted. They were sent some preliminary results and were asked to comment on those results. The following responses were obtained and were factored into the results presented in figures 3 through 16.

1. In general, at low drag levels, a balance sized to have high drag level capability does not give adequate resolution or precision.

2. In transonic or rotational flow balance drag data can be more accurate than the total probes of a wake rake because a rake can not capture all of the losses.

3. When experimental angle-of-attack increments are too coarse to accurately derive reasonable values for C_{d_0}, assume that $C_{d_0} = C_{d_{\alpha=0}}$. Note that the zero-lift angle of attack for the SC1095 and SC1094R8 are –0.3° and –1.4°, respectively (ref. 11).

4. Integration of surface pressures on a model with a limited number of pressure taps is generally inaccurate.

5. Tunnel wall porosity affects C_{l_α} and $C_{l_{max}}$ and is discussed in the published report for Experiment 5 (ref. 5).

Discussion

Discussion is warranted on the Group 1 and Group 2 tolerances relative to accuracies in experimental measurements. To illustrate this, consider the derivation of lift from measured data as

$$L_{measured} = C_{l_{measured}} \frac{1}{2}\rho V^2 S \qquad (1)$$

where

$$C_{l_{measured}} = \frac{1}{\beta C}\int_0^c \left(C_{P_l} - C_{P_u}\right)dx$$

Assuming there are inaccuracies in the pressure transducer measurements in the form of a simple bias error, P_{error}, then

$$C_{P_l} = \frac{P_l - P + P_{error}}{\frac{1}{2}\rho V^2}$$

$$C_{P_u} = \frac{P_u - P - P_{error}}{\frac{1}{2}\rho V^2}$$

substituting

$$\frac{\beta L_{measured}}{S} = \frac{1}{C}\int_0^c \left(P_l - P_u\right)dx + 2P_{error} \qquad (2)$$

$$\left.\frac{\beta \Delta L_{measured}}{S}\right|_{error} = 2P_{error} \qquad (3)$$

Note that on the UH-60 Phase II Airloads Program pressure blade, the transducer measurements are accurate to within 0.1% of their maximum range of 20 psia. Thus,

$$\left.\frac{\beta \Delta L_{measured}}{S}\right|_{error}$$

equals 0.04 psia.

Now, consider the maximum error in the calculation of lift for a given group tolerance, as follows:

$$\left.\frac{\beta \Delta L_{Group\ 1}}{S}\right|_{error} = \left(\beta C_{l_\alpha} + 0.0005\right)\Delta\alpha \frac{1}{2}\rho V^2 - \left(\beta C_{l_\alpha} - 0.0005\right)\Delta\alpha \frac{1}{2}\rho V^2 \qquad (4)$$

$$\left.\frac{\beta \Delta L_{Group\ 1}}{S}\right|_{error} = 0.001\Delta\alpha \frac{1}{2}\rho V^2 \qquad (5)$$

$$\left.\frac{\beta \Delta L_{Group\ 2}}{S}\right|_{error} = 0.008\Delta\alpha \frac{1}{2}\rho V^2 \qquad (6)$$

Figure 17 is a plot of equations (3), (5), and (6) versus airspeed for a nominal angle-of-attack range of 1.0°. It can be seen that a large region exists beyond M = 0.40, which indicates that the assumed bias error in lift measured by the UH-60 pressure blade is smaller than the maximum possible error that can be obtained when calculating lift using Group 2 wind tunnel data. This is not the case for Group 1 quality data.

The purpose of figure 17 is to show that Group 1 data are sufficiently accurate to use in predicting UH-60 airloads. It is not meant to imply that Group 2 quality data are not sufficiently accurate. Such a determination is dependent on many factors, such as:

1. The desired accuracy of the predictions.

2. Aspects of the physical representation of the UH-60 that are inaccurate or cannot be modeled, that overshadow any inaccuracies realized by using Group 2 quality data.

3. Limitations of the comprehensive analytical model that may overshadow any inaccuracies realized by using Group 2 quality data.

Until these issues have been resolved, it cannot be determined whether Group 2 data are sufficiently accurate for their intended use in the UH-60 model.

This last issue is the primary concern when evaluating lifting-line methods employed in comprehensive rotorcraft analyses. It is not known if current methodologies are sensitive to errors introduced by using Group 2 quality data. This question forms the basis for the recommendations discussed in the next section.

Also, it should be noted that consistent Group 2 quality data do not exist beyond speeds of roughly M = 0.70 or M = 0.80, depending on the airfoil. The advancing blade Mach numbers for the SC1095 and the SC1094R8 airfoils are 1.012 and 0.90, respectively, at the "do not exceed" velocity of 192 knots and 20,000 feet.

There are currently many sources of SC1095 and SC1094R8 data circulating throughout the aerospace community in a variety of different formats. Not all the sources of data are traceable. In fact, many of those sources may be inaccurate. An easy way to check the accuracy of those data sets would be to plot the variation of C_{l_α} and C_{d_0} versus Mach number against the results presented in this report for either airfoil. Alternately, the results presented in this report can be approximated using semi-empirical expressions developed by McCroskey (ref. 10) for the NACA 0012 airfoil in supersonic flow and by Smith (ref. 12) for a variety of different airfoils in subsonic flow. Correlation of the semi-empirical expressions with the results presented in this report are shown in figures 6 and 7 for the SC1095 airfoil, and in figures 13 and 14 for the SC1094R8 airfoil. The combined, or composite, McCroskey-Smith expressions used to generate the approximations shown on those figures are presented in the appendix.

Conclusions

The primary motivation for this evaluation was to prepare for rigorous analysis methodology validation as part of the UH-60 Phase II Airloads Program. Analysis methodology validation consists of assessing and improving state-of-the-art comprehensive analytical models through exhaustive correlative studies in performance, dynamics, and rotor structural loads and airloads. In order to productively assess and improve the theories and assumptions employed in comprehensive analytical models, accurate vehicle representations must be established. The main rotor blade airfoil section characteristics are among the most important parts of the vehicle representation. Ultimately, the improvements in analysis methodology and in vehicle representations will be judged relative to improvements in the correlation of predictions with experimental measurements.

This report shows that the most accurate data are Group 2 quality. The experiments that generated this quality of data were performed in 1982 at the 11-Foot Wind Tunnel Facility at NASA Ames Research Center and in 1985 at the 6-Inch by 22-Inch Transonic Wind Tunnel Facility at Ohio State University. It has not been determined whether Group 2 quality data are sufficiently accurate to use in comprehensive analytical models to predict experimentally measured airloads data.

Furthermore, the McCroskey methodology used to evaluate the airfoil data tend to work best when there are large amounts of data, a significant portion of which are Group 1 and 2 quality throughout the desired ranges of Mach and Reynolds numbers. Although it can be argued that a significant percentage of the data presented herein are Group 2 quality, they are not nearly as much as desired, nor are they as consistent as desired. Therefore, it is important that further synthesis and experimentation be performed in order to generate Group 1 quality data. This conclusion warrants specific recommendations, discussed in detail in the next section.

Recommendations

The results presented in this report show that the most accurate data are Group 2 quality. It has not been determined whether this is of sufficient accuracy to use in predicting UH-60 airloads. If it is determined that the accuracy is not sufficient, then the following recommendations should be interpreted as requirements.

It is recommended that further wind tunnel experimentation be performed to obtain Group 1 quality data, and that this effort be preceded by a synthesis similar to that performed by Tanner (ref. 13). Candidate facilities for the experimentation include those shown by McCroskey to produce Group 1 quality data. However, speed, angle-of-attack range, and Reynolds number range should be considered before choosing a wind tunnel. It is understood that the aforementioned wind tunnels may not be able to satisfy the high speed requirement, and this should weigh heavily in the selection of a wind tunnel facility. Further, large positive and negative angle-of-attack ranges should be considered in increments small enough to identify the exact values for $C_{l_{max}}$ and C_{d_o}. It is important that both the synthesis and experimentation be performed for full scale Reynolds numbers. Actual SC1095 and SC1094R8 contours as measured on the Phase II Airloads Program pressure instrumented blade should be used if new wind tunnel models of those airfoil sections are to be fabricated. Determination of several critical parameters should be the priority of both the synthesis and the experimentation. These parameters include, but are not limited to, $C_{l_{\alpha_{max}}}$, $C_{l_{\alpha_{min}}}$, $C_{l_{\alpha_{recovered}}}$, M_{DD}, $C_{d_{o_{max}}}$, the maximum values of $(L/D)_{max}$ and $C_{l_{max}}$, and the Mach numbers at which they occur.

Finally, it is recommended that a methodology be developed to evaluate pitching moment coefficient, and that the synthesis and additional experimentation treat pitching moment coefficient with the same level of detail as lift and drag coefficient.

Appendix

For the SC1095 airfoil data, the combined, or composite, McCroskey-Smith expressions are superimposed on figures 6 and 7. In the M ≤ 0.6 region the empirical log curve fit of the C_{l_α} data is given as

$$\beta C_{l_\alpha} = 0.0531 + 0.0081 \log(R_e) \qquad (7)$$

The expressions developed by Smith for C_{l_α} are $0 \le M \le (M_1 = 0.84)$

$$C_{l_{\alpha(\le M_1)}} = C_{l_{\alpha(M=0, R_c=6\times10^6)}} \left\{\mu + \frac{t/c}{1+t/c}\left[\mu(\mu-1) + \frac{1}{4}(\gamma+1)\left(\mu^2-1\right)^2\right]\right\} \qquad (8)$$

and $M_1 < M \le 0.93$

$$C_{l_{\alpha(>M_1)}} = C_{l_{\alpha(\le M_1)}} - \frac{\partial C_{l_a}}{\partial M}(M - M_1) \qquad (9)$$

where

$$\frac{\partial C_{l_\alpha}}{\partial M} = 5.4$$

and the expression developed by McCroskey for C_{l_α} is $0.93 < M \le 1.1$

$$C_{l_\alpha} = 0.055\left[(\gamma+1)M^2(t/c)\right]^{-1/3} \qquad (10)$$

In the M ≤ 0.6 region the log empirical curve fit of the C_{d_o} data is given as

$$C_{d_o} = 0.0143 - 0.0010 \log(R_c) \qquad (11)$$

The expressions developed by Smith for C_{d_o} are $0 \le M \le (M_{DD} = 0.8)$

$$C_{d_o} = c_f\left\{S_A \frac{L}{c}\left(1+\frac{c_s}{c_F}\right) + \frac{K\left[(0.01745)|\alpha_{ZL}|\right]^{2.7}}{c_{f_{R_{N_o}}=6\times10^6}}\right\} \qquad (12)$$

where

$$c_f = \frac{0.455}{\left[\log\left(R_{N_o}\frac{1}{2}\frac{L}{c}\sqrt{S_A}\right)\right]^{2.58}}$$

$$\alpha_{ZL} = -0.3 \text{ deg}$$

$$S_A = 1.14$$

$$\frac{L_P}{c} = 2.022$$

$$\frac{c_S}{c_F} = 0.02$$

$$R_{N_o} = R_c = 6\times10^6$$

$$K = 2.12$$

and $M_{DD} < M < 1.0$

$$C_{d_{o(>M_{DD})}} = C_{d_{o(M_{DD})}} + \frac{\partial C_{d_o}}{\partial M}(M - M_{DD}) \qquad (13)$$

where

$$\frac{\partial C_{d_o}}{\partial M} = 0.4$$

and the expression developed by McCroskey for C_{d_o} is $1.0 \le M \le 1.1$

$$C_{d_o} = C_{d_{0(<M_{DD})}} + a(t/c)^{5/3}\left[(\gamma+1)M^2\right]^{-1/3} \quad (14)$$

where

$$a = 5.0$$

For the SC1094R8 airfoil data, all of which were subsonic data, the Smith expressions are superimposed on figures 13 and 14. In the $M \le 0.55$ region the empirical log curve fit of the C_{l_α} data is given as

$$\beta C_{l_\alpha} = 0.0977 + 0.0009 \log(R_e) \quad (15)$$

The expressions developed by Smith for C_{l_α} are $0 \le M \le (M_1 = 0.83)$

$$C_{l_\alpha} = C_{l_\alpha\left(M=0, R_c=10^6\right)} \left\{\mu + \frac{t/c}{1+t/c}\left[\mu(\mu-1) + \frac{1}{4}(\gamma+1)\left(\mu^2-1\right)^2\right]\right\} \quad (16)$$

and $M_1 < M < 0.9$

$$C_{l_{\alpha(>M_1)}} = C_{l_{\alpha(\le M_1)}} - \frac{\partial C_{l_\alpha}}{\partial M}(M - M_1) \quad (17)$$

where

$$\frac{\partial C_{l_\alpha}}{\partial M} = 5.4$$

In the $M \le 0.55$ region, the empirical log curve fit of the C_{d_0} data is given as

$$C_{d_o} = 0.0146 - 0.0009 \log(R_c) \quad (18)$$

The expressions developed by Smith for C_{d_0} are $0 \le M \le (M_{DD} = 0.7)$

$$C_{d_o} = c_f\left\{S_A \frac{L}{c}\left(1+\frac{c_s}{c_F}\right) + \frac{K\left[(0.01745)|\alpha_{ZL}|\right]^{2.7}}{c_{f_{R_{N_o}} = 6\times10^6}}\right\} \quad (19)$$

where

$$c_f = \frac{0.455}{\left[\log\left(R_{N_o} \frac{1}{2}\frac{L}{c}\sqrt{S_A}\right)\right]^{2.58}}$$

$$\alpha_{ZL} = -1.4 \text{ deg}$$

$$S_A = 1.14$$

$$\frac{L_p}{c} = 2.022$$

$$\frac{c_s}{c_F} = 0.02$$

$$R_{N_o} = R_e = 6\times10^6$$

$$K = 2.12$$

and $M_{DD} < M < 0.9$

$$C_{d_{o(>M_{DD})}} = C_{d_{o(\le M_{DD})}} + \frac{\partial C_{d_o}}{\partial M}(M - M_{DD})$$

where

$$\frac{\partial C_{d_o}}{\partial M} = 0.15$$

The above expressions compare well with the noted trends of C_{l_α} and C_{d_0} versus Mach number for both the airfoils, with a small discrepancy noted in C_{l_α} for the SC1094R8 data between M = 0.5 and M = 0.8. These expressions are meant only to quantify observed trends. An analysis of the correlation is not within the scope of this paper.

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Table 1. SC1095 and SC1094R8 wind tunnel data reference list

Experiment facility report no.	Mach range	R_c range (range × 10^6)	Model and tunnel dimensions	Remarks
Experiment 1 LSWT 8 ft UARL M432170-1	0.3–0.75	2.52–4.97	b/c = 2.06 h/c = 5.8	SC1095 Limited rights data, balance, wake
Experiment 2 LSWT 8 ft UTRC75-121	0.3–0.75	2.54–4.94	b/c = 7.75 h/c = 5.8	SC1095 Limited rights data, pressure, wake
Experiment 3 Ohio State 6 in. × 22 in. SER-760603	0.3–0.85	2.88–7.57	b/c = 3.67 h/c = 1.0	SC1095, SC1094R8 Partial limitation, pressure, including tripped data
Experiment 4 NRC high speed icing facility NASA CR-3910	0.3–0.87	1.80–4.60	b/c = 2.0 h/c = 2.0	SC1095, SC1094R8 Domestic limitation, pressure, wake
Experiment 5 NSRDC 7 ft × 10 ft SER-50977	0.3–1.1	1.29–3.96	b/c = 7.5 h/c = 5.25	SC1095 Balance, pressure, wake, including strut data
Experiment 6 LaRC 6 in. × 28 in. NASA TP-1701	0.35–0.9	1.60–6.70	b/c = 1.94 h/c = 9.03	SC1095, SC1094R8 Pressure, +3° (up) TE tabs
Experiment 7 Ames 2 ft × 2 ft NASA TM-86719	0.2–0.88	1.87–4.00	b/c = 4.0 h/c = 4.0	SC1095 Pressure
Experiment 8 Ames 11 ft NASA CR-166587	0.3–1.1	3.60–6.05	b/c = 8.21 h/c = 8.21	SC1095, SC1094R8 Balance, pressure, wake
Experiment 9 Ames 7 ft × 10 ft NASA TM-84245	0.11–0.3	1.44–3.88	b/c = 3.49 h/c = 5.0	SC1095 Pressure, wake

LSWT = large-scale wind tunnel
NSRDC = Naval Ship Research and Development Center

Table 2. Wind tunnel facility reputation and wall corrections used in the experiments

Experiment	Wind tunnel	Documented reputation[a]	Tunnel wall corrections
Experiment 1	LSWT 8 ft	Group 3	Linear wall corrections, solid walls
Experiment 2	LSWT 8 ft	Group 3	Linear wall corrections, solid walls
Experiment 3	Ohio St. 6 in. × 22 in.	Group 4	Independent plenums for top and bottom walls, porous walls
Experiment 4	NRC Icing		Linear plenum, surface corrections, and high turbulence levels
Experiment 5	NSRDC 7 ft × 10 ft	Group 4	Large lift interference, with and without wake drag corrections, high porosity, and slotted walls
Experiment 6	LaRC 6 in. × 28 in.	Group 4 (capable of Group 3)	AOA corrected, side wall boundary layer effects on shock position, and $C_{l_{max}}$, and slotted walls
Experiment 7	Ames 2 ft × 2 ft		AOA corrections and slotted walls
Experiment 8	Ames 11 ft		Wall corrections but none on AOA, and slotted walls
Experiment 9	Ames 7 ft × 10 ft	Group 2	Linear wall corrections, and solid walls

[a]Established by McCroskey in his evaluation of NACA 0012 data.

Table 3. Summary of results

		$C_{d_{o_{max}}}$	$C_{d_{o_{MDD}}}$	$(L/D)_{max}$	$C_{l_{max}}$	$C_{l_{\alpha_{max}}}$	$C_{l_{\alpha_{min}}}$	$C_{l_{\alpha_{recovered}}}$
SC1095	Value	0.09	0.0075	105	(1.35)	(0.24)	(0.05)	(0.085)
	Mach number	0.98	0.80	0.30	0.30	0.84	0.90	0.93
SC1094R8	Value	*	0.0077	(115)	(1.75)	0.20	*	*
	Mach number		0.70	0.30	0.30	0.83		

( ) denotes scattered data

* denotes no data

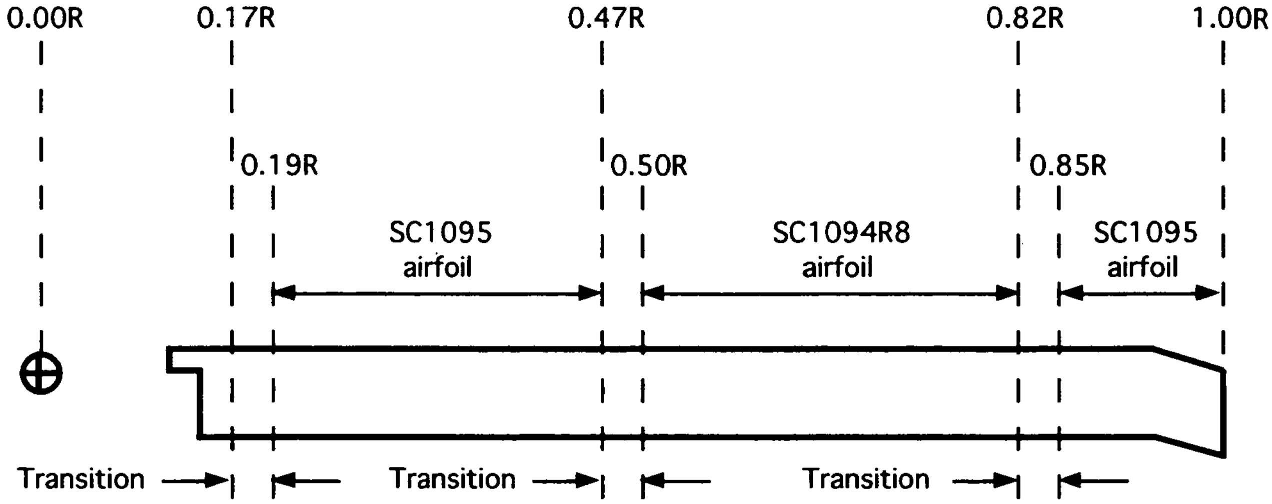

Figure 1. UH-60A Black Hawk main rotor blade airfoil section locations.

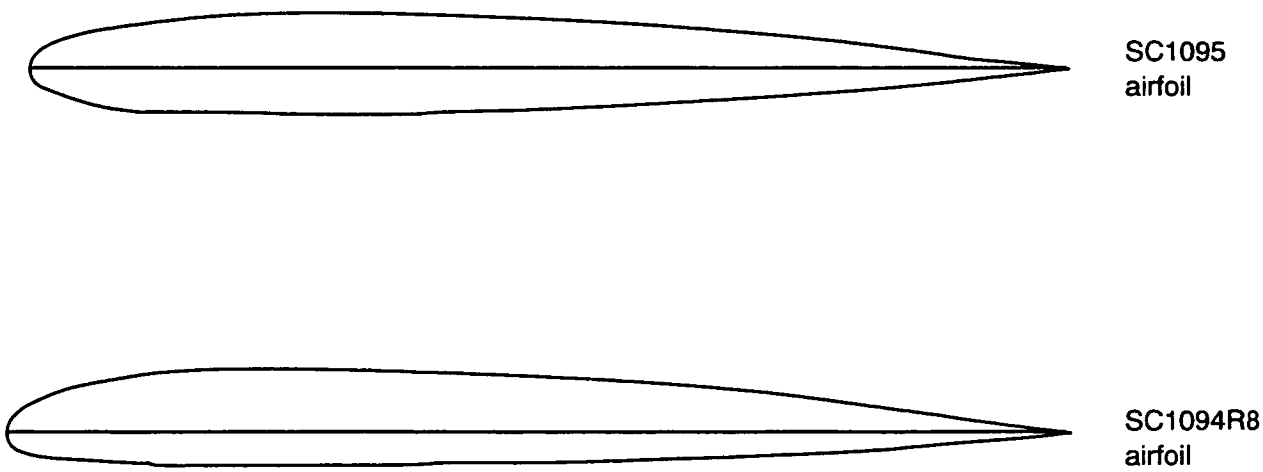

Figure 2. SC1095 and SC1094R8 airfoil sections.

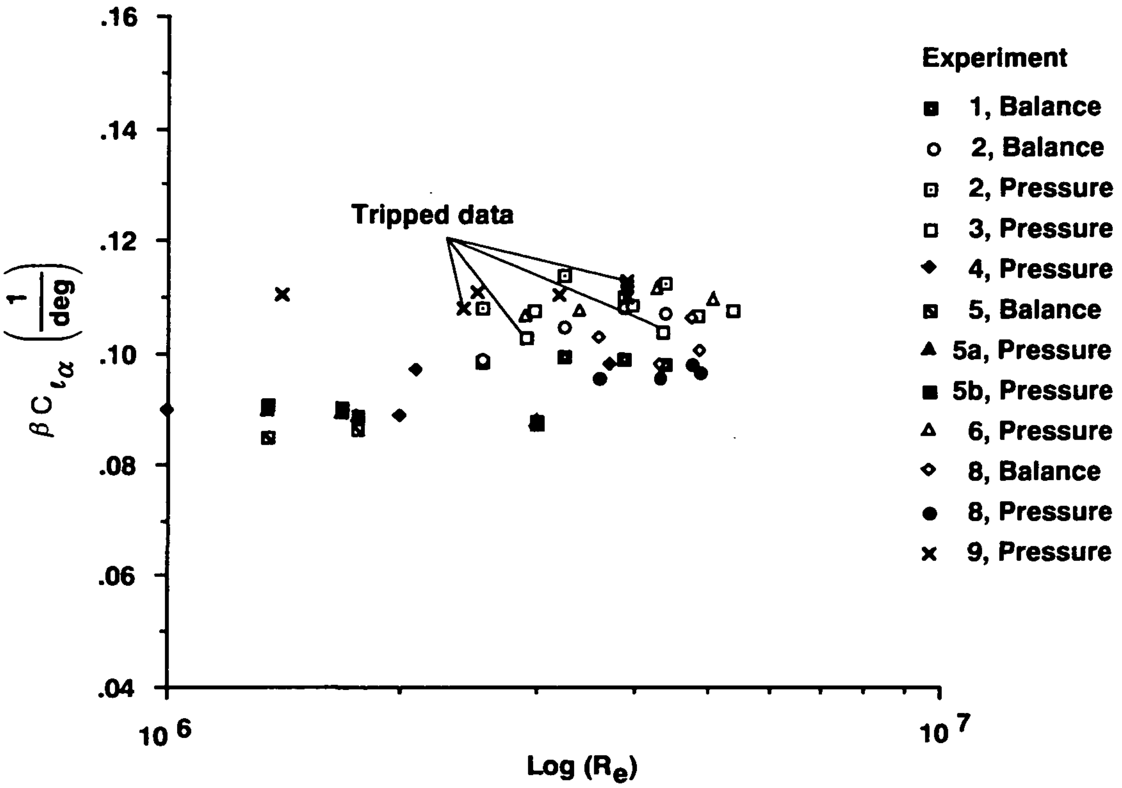

Figure 3. SC1095 Mach corrected lift curve slope versus Reynolds number, M < 0.6.

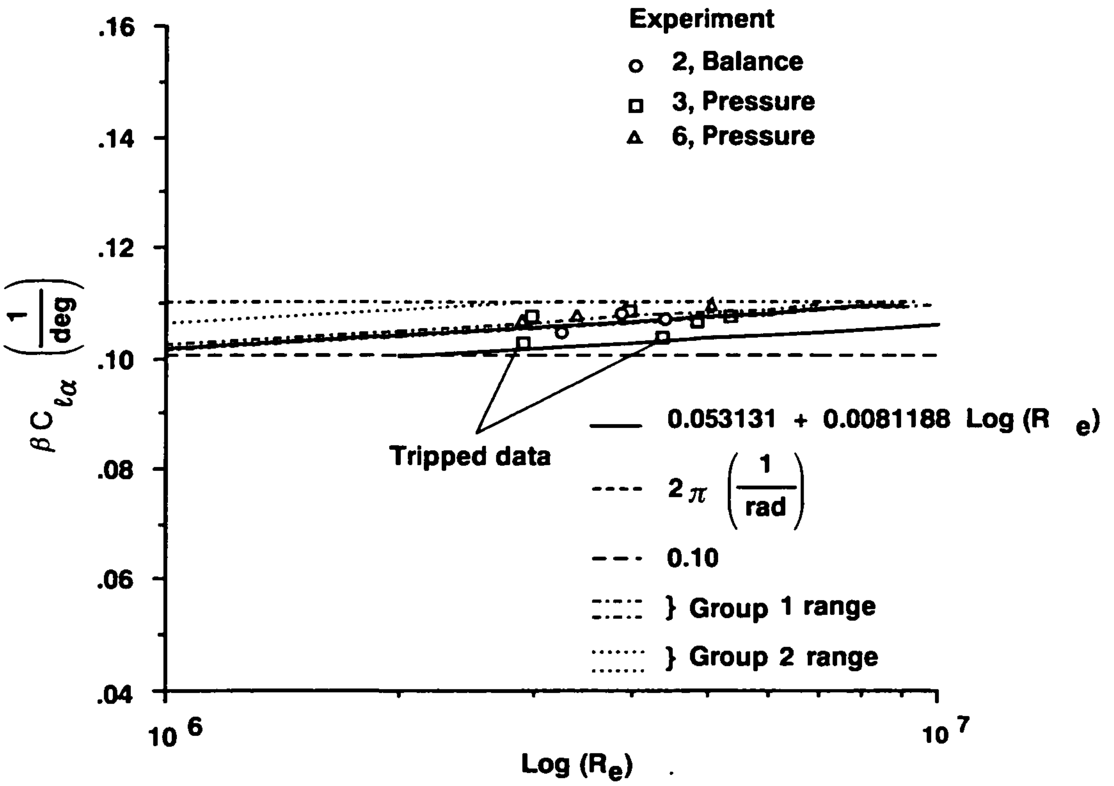

Figure 4. SC1095 Mach corrected lift-curve slope versus Reynolds number with Group 1 and Group 2 tolerances, M < 0.6.

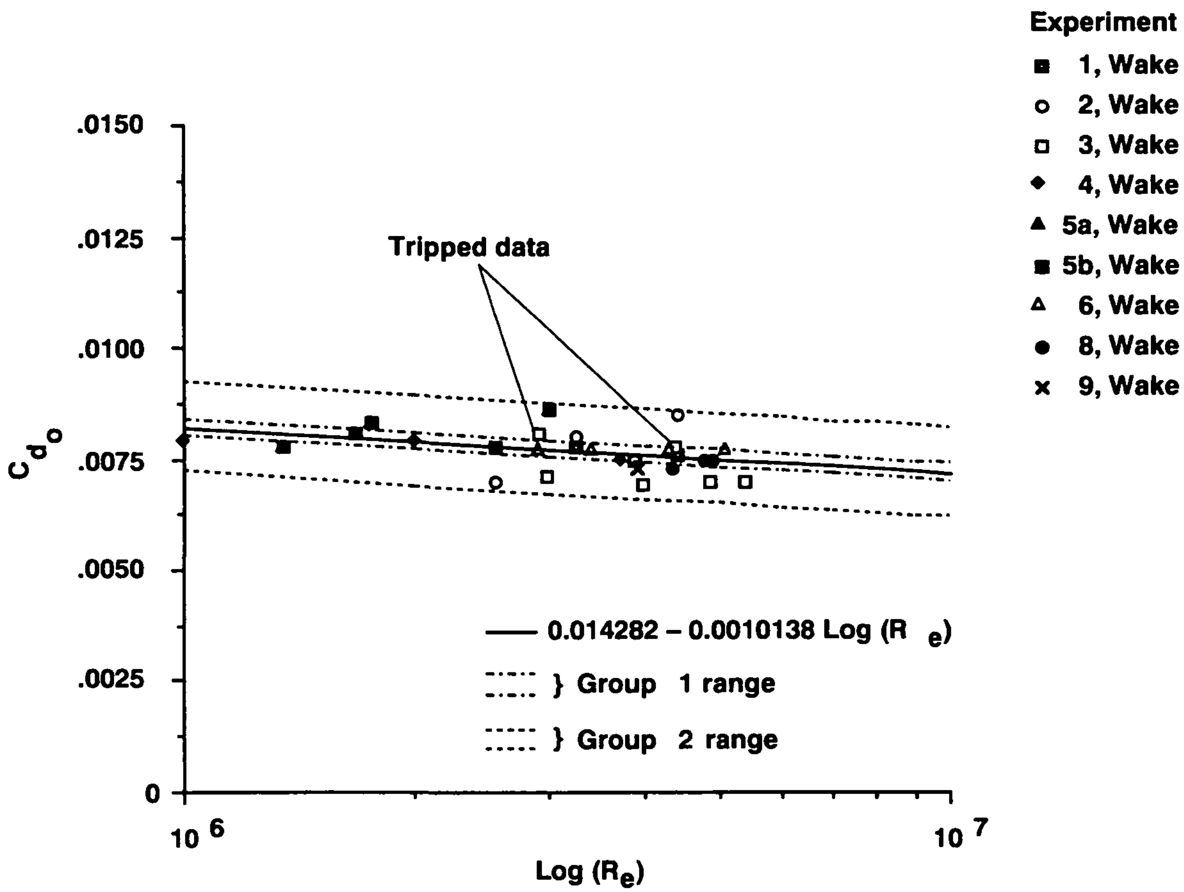

Figure 5. SC1095 drag coefficient at zero-lift versus Reynolds number with Group 1 and Group 2 tolerances, M < 0.6.

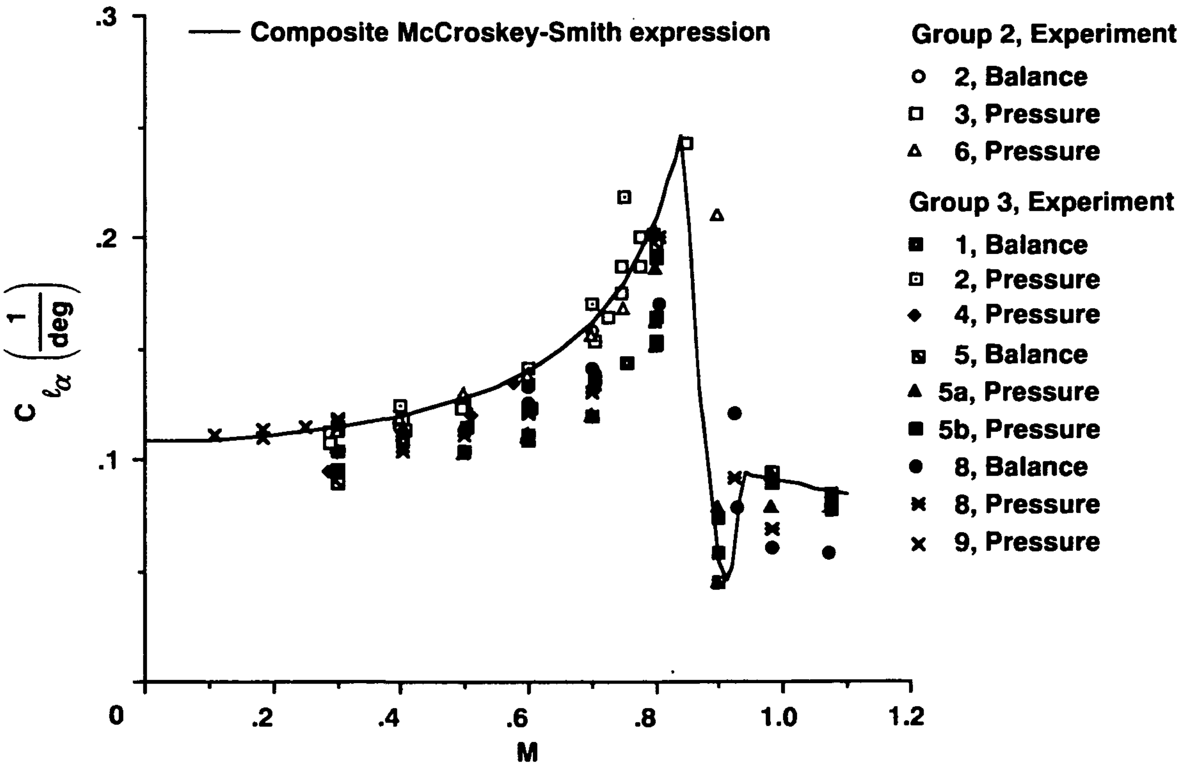

Figure 6. SC1095 lift-curve slope versus Mach number.

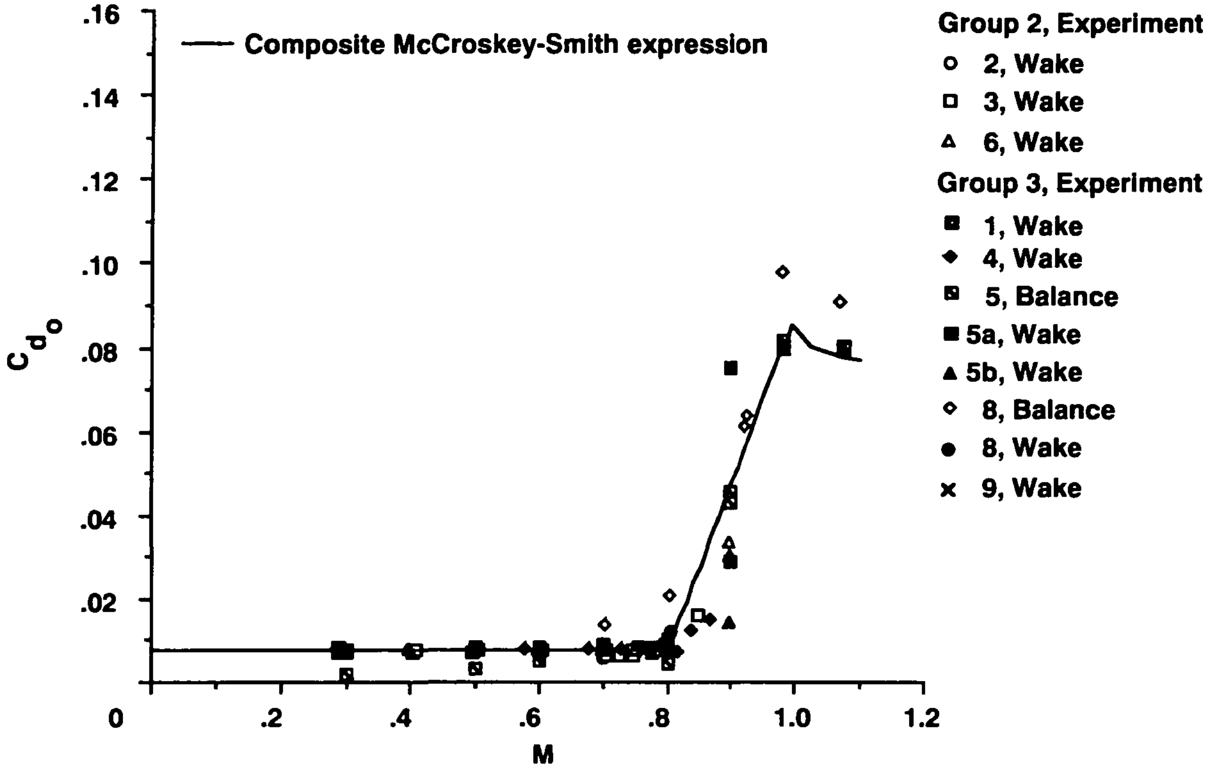

Figure 7. SC1095 drag coefficient at zero lift versus Mach number.

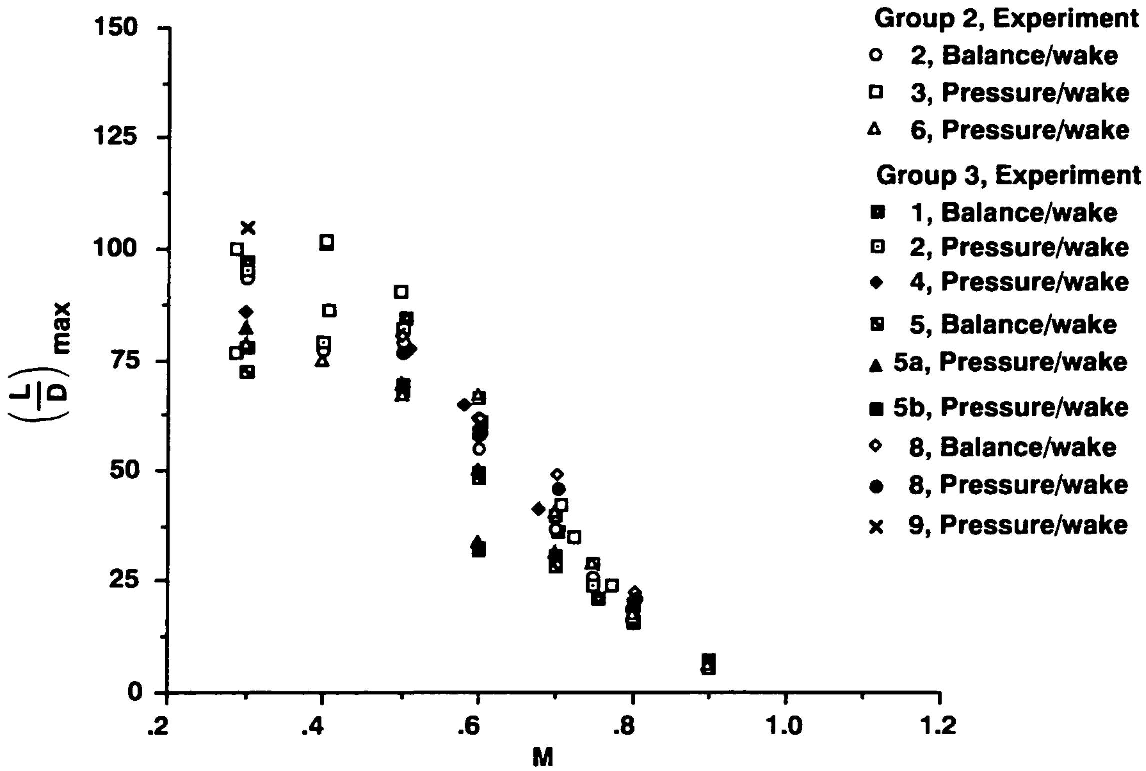

Figure 8. SC1095 maximum lift-to-drag ratio versus Mach number.

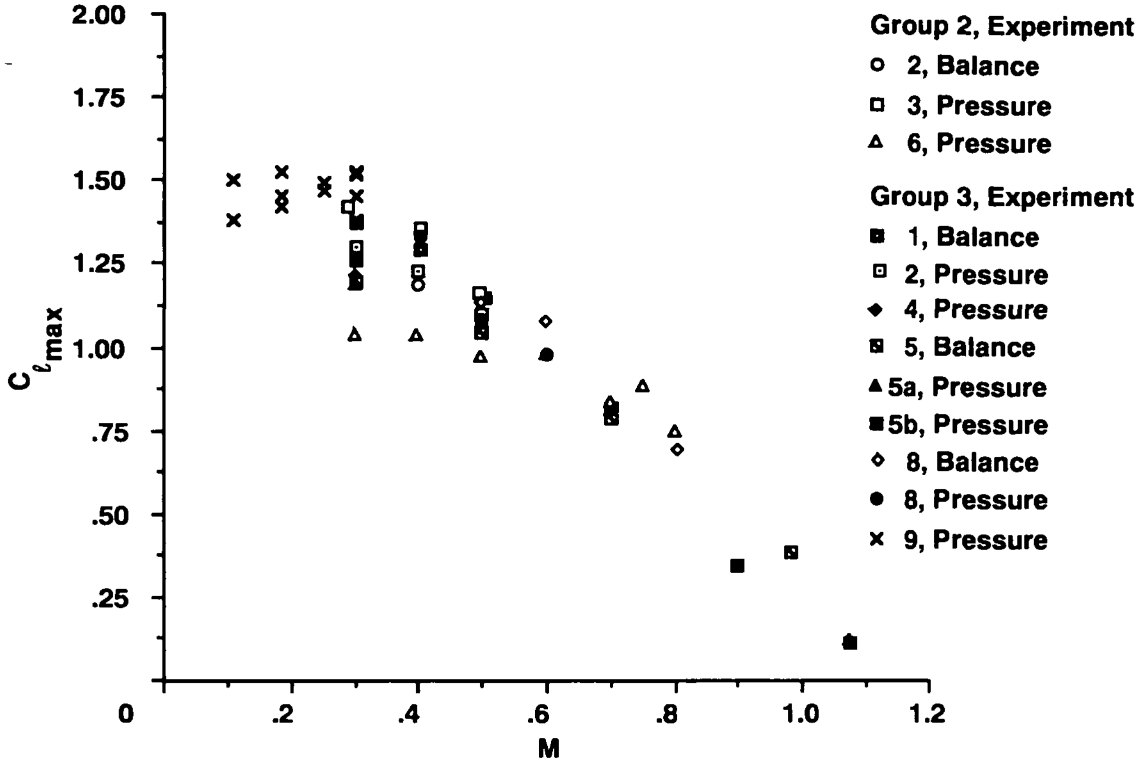

Figure 9. SC1095 maximum lift coefficient versus Mach number.

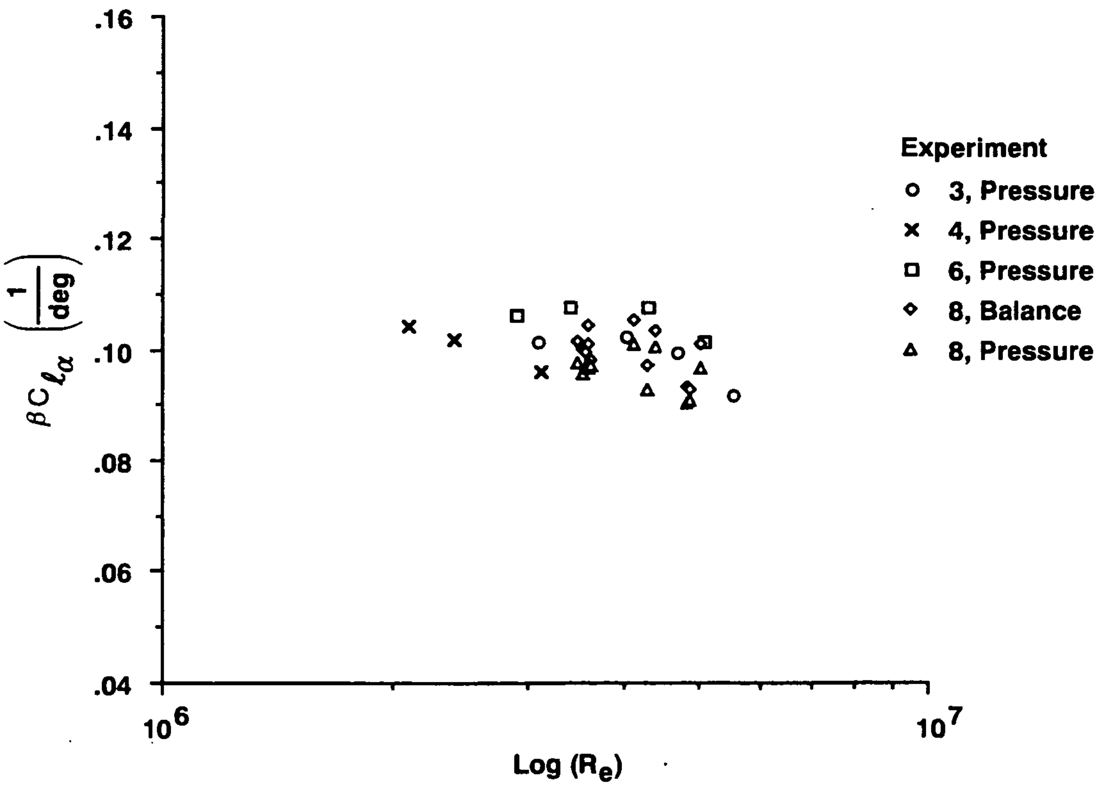

Figure 10. SC1094R8 Mach corrected lift curve slope versus Reynolds number, M < 0.55.

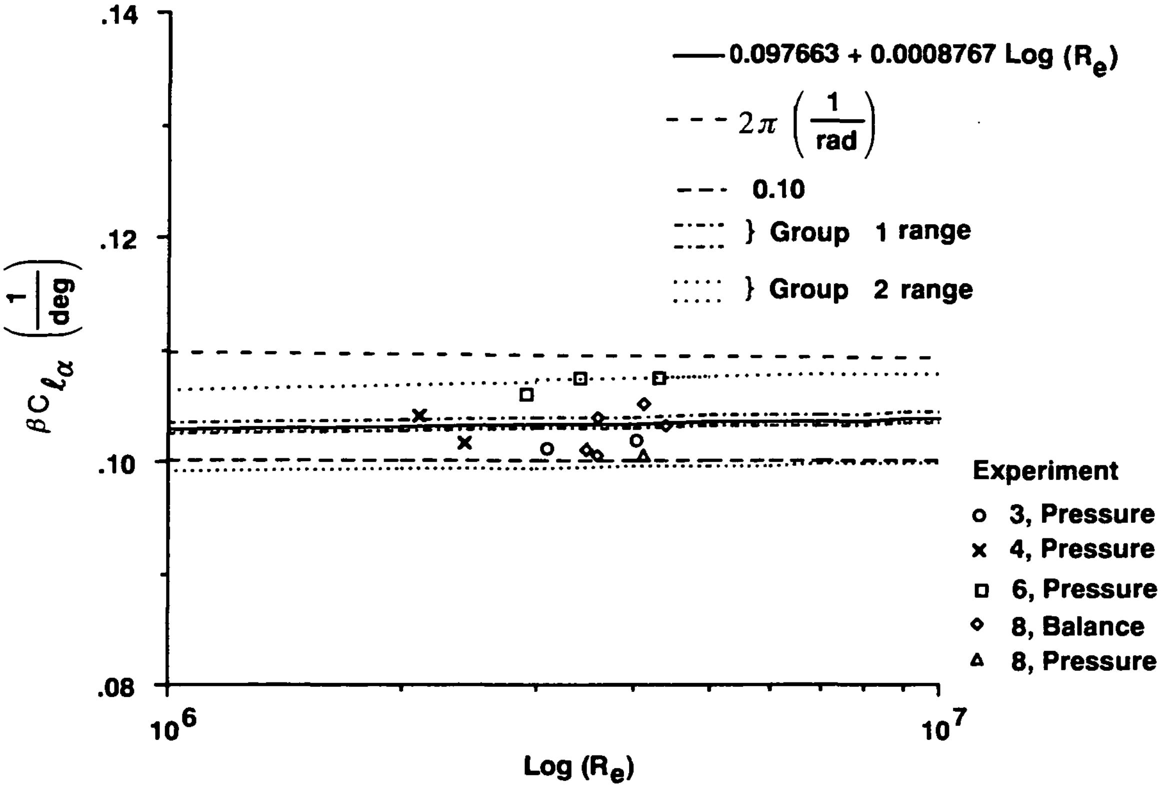

Figure 11. SC1094R8 Mach corrected lift-curve slope versus Reynolds number with Group 1 and Group 2 tolerances, M < 0.55.

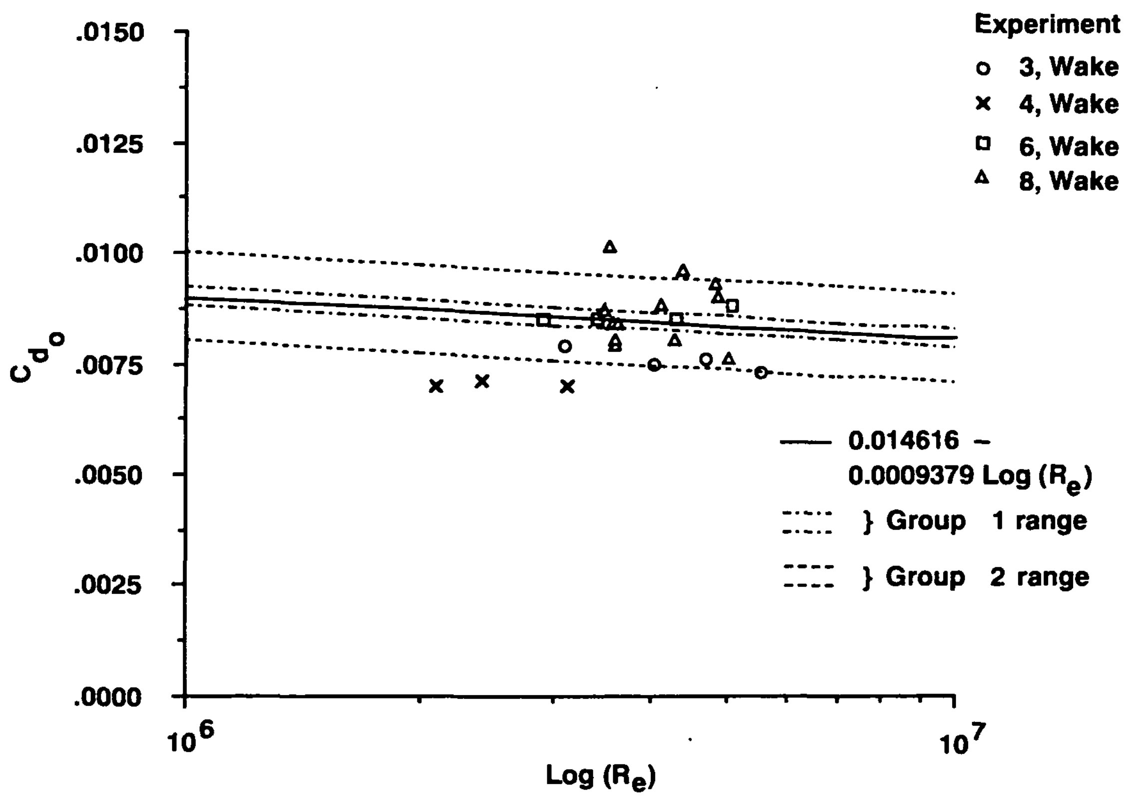

Figure 12. SC1094R8 drag coefficient at zero-lift versus Reynolds number with Group 1 and Group 2 tolerances, M < 0.55.

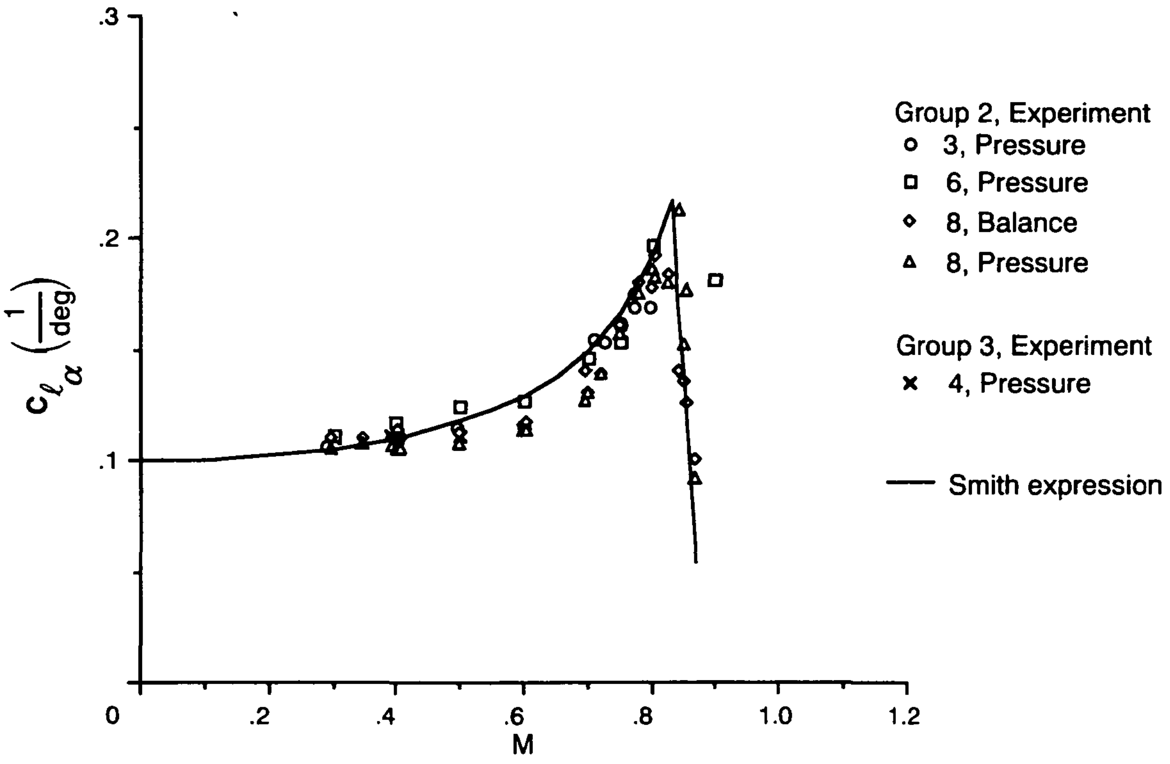

Figure 13. SC1094R8 lift-curve slope versus Mach number.

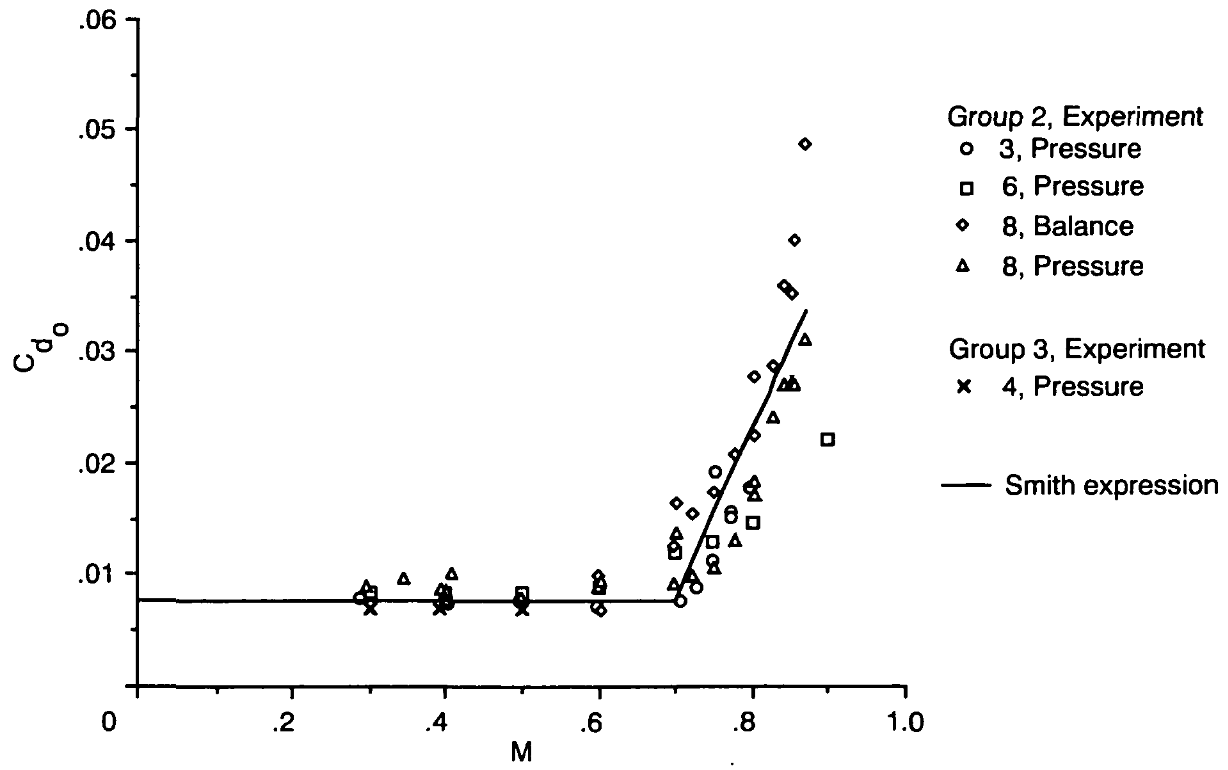

Figure 14. SC1094R8 drag coefficient at zero lift versus Mach number.

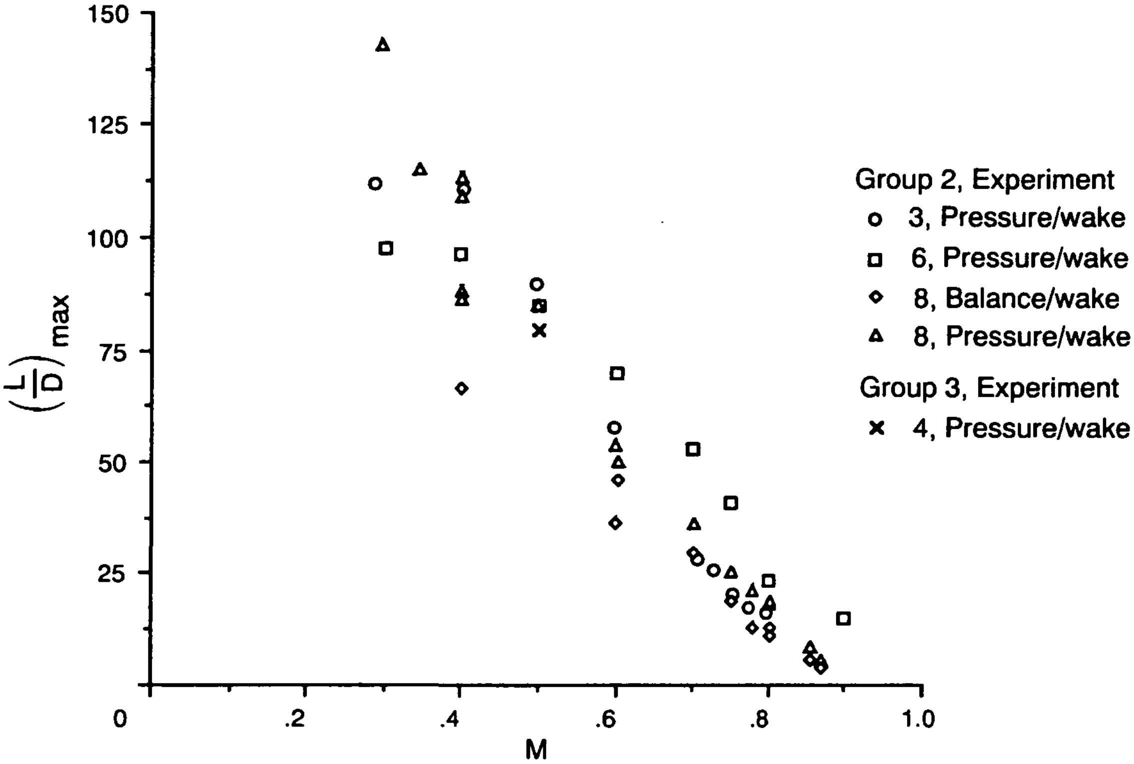

Figure 15. SC1094R8 maximum lift-to-drag ratio versus Mach number.

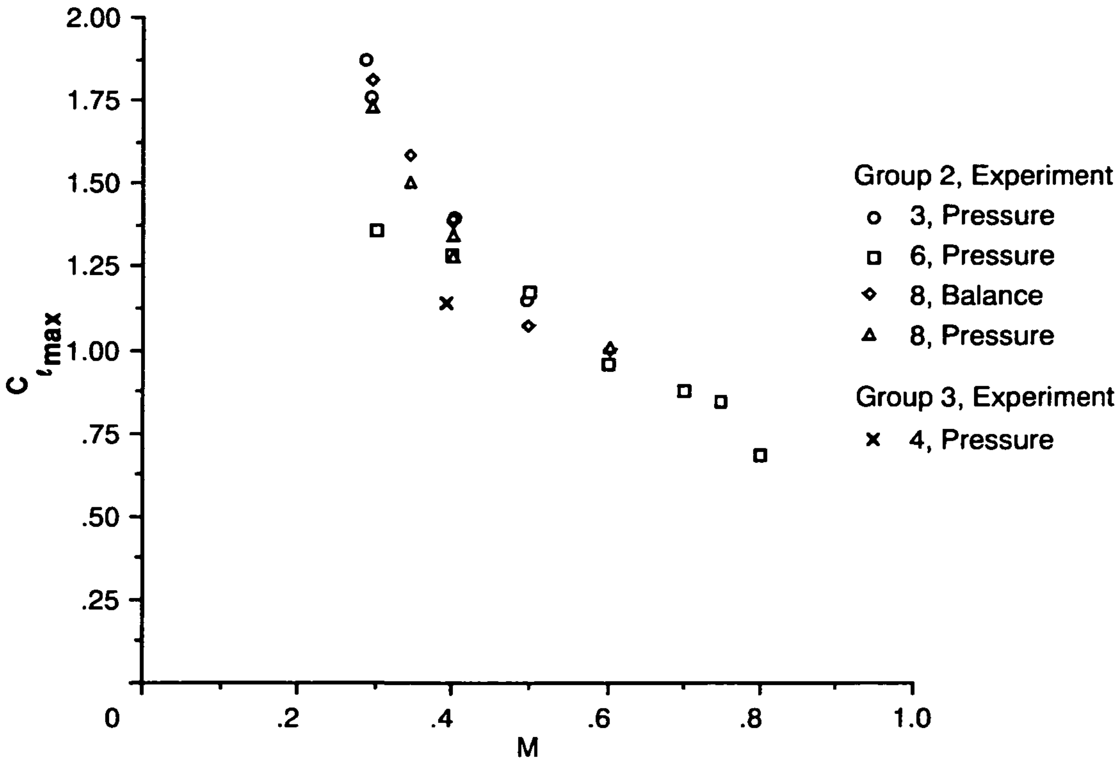

Figure 16. SC1094R8 maximum lift coefficient versus Mach number.

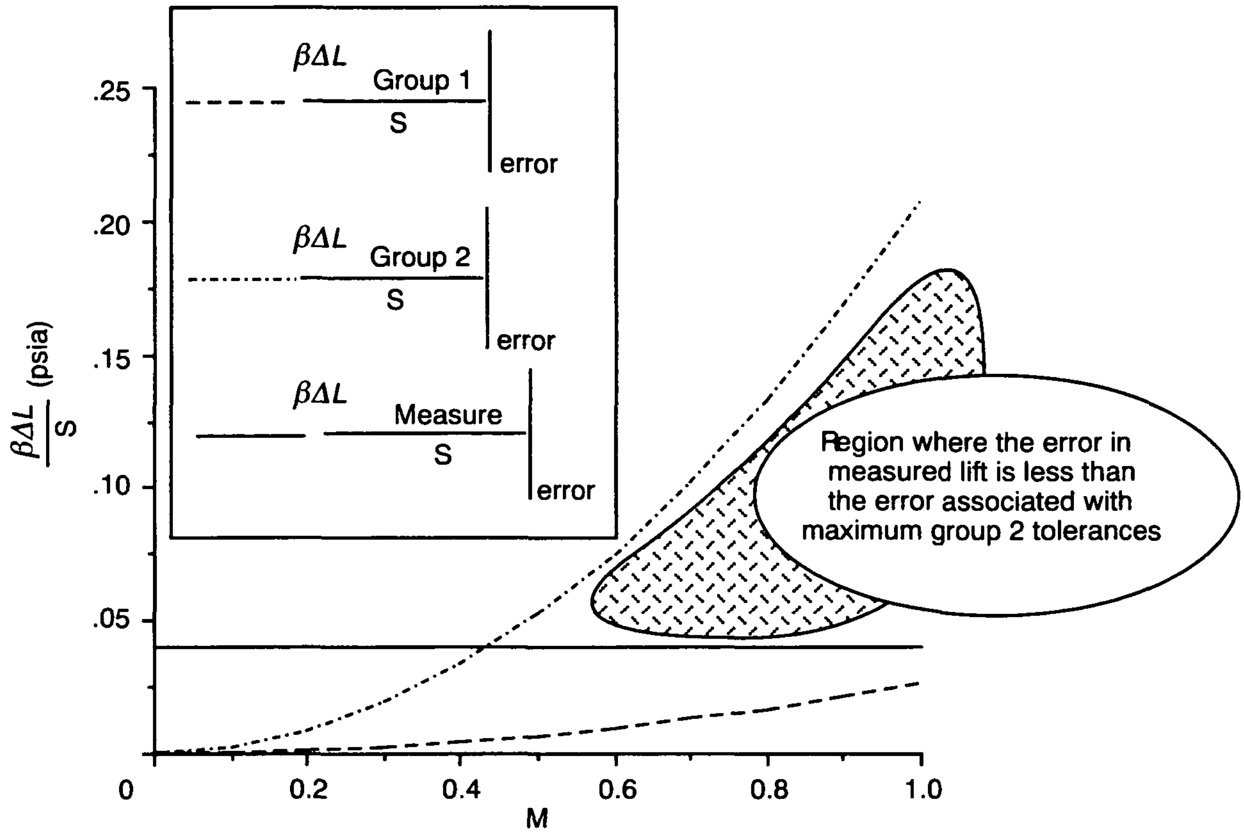

Figure 17. Comparison of the error in lift derived from measured pressure transducer steady bias error, and Group 1 and Group 2 tolerances versus Mach number for a nominal 1 degree change in angle of attack.

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13. ABSTRACT *(Maximum 200 words)*

Many current comprehensive rotorcraft analyses employ lifting-line methods that require main rotor blade airfoil data, typically obtained from wind tunnel tests. In order to effectively evaluate these lifting-line methods, it is of the utmost importance to ensure that the airfoil section data are free of inaccuracies. A critical assessment of the SC1095 and SC1094R8 airfoil data used on the UH-60 main rotor blade was performed for that reason. Nine sources of wind tunnel data were examined, all of which contain SC1095 data and four of which also contain SC1094R8 data. Findings indicate that the most accurate data were generated in 1982 at the 11-Foot Wind Tunnel Facility at NASA Ames Research Center and in 1985 at the 6-inch-by-22-inch transonic wind tunnel facility at Ohio State University. It has not been determined if data from these two sources are sufficiently accurate for their use in comprehensive rotorcraft analytical models of the UH-60. It is recommended that new airfoil tables be created for both airfoils using the existing data. Additional wind tunnel experimentation is also recommended to provide high quality data for correlation with these new airfoil tables.

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