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METHODOLOGY FOR MATCHING EXPERIMENTAL AND COMPUTATIONAL AERODYNAMIC DATA

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Abstract

Correction factor methodologies have been developed which use steady experimental or analytical pressure or force data to correct steady and unsteady aerodynamic calculations. Three methods of calculating correction factors have been developed to match steady surface pressure distributions, to match airfoil section forces and moments, and to match total forces and moments. Data for a rectangular supercritical wing that was previously tested in the NASA Langley Research Center Transonic Dynamics Tunnel have been used to determine correction factors to match surface pressure distributions for a range of Mach numbers. These correction factors have also been applied to unsteady aerodynamic calculations and comparisons have been made with oscillatory experimental data for a range of reduced frequencies at several Mach numbers.

Nomenclature

c	reference chord
ΔC_{p_α}	derivative of lifting pressure coefficient with respect to angle of attack
C_ℓ	section lift coefficient
C_L	total lift coefficient
C_m	section pitching moment coefficient
C_M	total pitching moment coefficient
E	% maximum allowable error ÷ 100
F	section property or total force
j	objective function involving correction factors
J	objective function involving forces to be matched
k	reduced frequency $\left(= \frac{c\omega}{2V}\right)$
nb	number of boxes
nf	number of forces to be matched
ns	number of strips
x/c	fraction of chord measured from leading edge
Q	arbitrary objective function weighting factor
V	velocity
α	angle of attack
η	fraction of semispan from wing root
χ	correction factor
ω	frequency (rad/sec)

Subscripts

D	value of desired force to be matched
i,k	integer indices
tot	total

Superscripts

a	analytical
e	experiment
( )'	derivative of ( ) with respect to ξ

Introduction

This paper describes the development of correction factor methodologies which use steady experimental or analytical pressure or force data to correct steady and unsteady aerodynamic calculations. The motivation for this research is that methods are still needed to improve routine analytical calculations of steady and unsteady pressures and forces using high quality aerodynamic data. Correction factors are multipliers which are applied to aerodynamic downwashes or pressures in aerodynamic calculations to achieve a specified desired objective. For example, figure 1 shows a typical aerodynamic box layout required to calculate unsteady aerodynamic forces using the Doublet Lattice Method (DLM) [1], where the correction factors would be applied to the individual boxes.

Modifying analytical aerodynamic calculations using experimental aerodynamic data is not new. Giesing, Kalman and Rodden [2] developed a correction factor technique to modify Doublet Lattice aerodynamics by matching total experimental force data. They formulated the problem such that the total forces were matched exactly while the change in the original analytical pressure distribution was minimized

Pitt [3] recently developed a correction factor technique which modified strip aerodynamic influence coefficients (AIC's) using data generated by the transonic full potential fluid dynamics program FLO28. Steady state section lift and moment were calculated by integrating the steady state pressures output from FLO28 over the chord. The derivatives with respect to angle of attack and control surface deflections were calculated using finite differences between separate cases of FLO28 where the geometry input had been modified to reflect the change in shape. Pitt used the correction factors derived from the steady data to modify unsteady Doublet Lattice calculations and his corrected unsteady aerodynamics resulted in improved transonic flutter predictions.

Three methods to calculate correction factors have been developed. The first approach described in this paper is to require a match between analytical and experimental surface pressure distributions, the second approach requires airfoil section characteristics to be matched and the third matches total forces or integrated pressures. The first and second approaches require interpolation of experimental pressure data from the measurement stations to the analytical box locations. For the first approach, the correction factors are calculated as the ratio of experimental to analytical pressure coefficients (ΔC_{p_α}) at discrete points on the wing. The second approach is similar but the correction factors are ratios of section properties, such as C_{ℓ_α}, C_{m_α}, etc. Optionally, optimization techniques can be used to determine correction factors which minimize section property errors and/or minimize the change in the analytical pressure distribution. The third approach uses optimization techniques to determine correction factors so that total forces, moments, or control derivatives are matched. This approach extends the work of Giesing, Kalman, and Rodden [2] by reformulating the optimization problem and introducing additional objective functions and constraints.

This paper describes the three methods of correction factor calculation but only presents results for the pressure distribution matching approach. The paper is organized in three sections. The first describes the methodologies, the second describes results and the final section presents some concluding remarks.

Correction Factors Methodology

Matching pressures

One approach to correction factor calculation is to compare the steady experimental and analytical pressure coefficients at the aerodynamic box locations. Pressure correction factors are then calculated for each individual box as the ratio of the experimental to analytical lifting pressure coefficient derivative ΔC_{p_α} as

$$\chi_p = \frac{\Delta C^{e}_{p_\alpha}}{\Delta C^{a}_{p_\alpha}} \tag{1}$$

This method therefore requires that experimental pressure data be interpolated to the analytical aerodynamic box locations. Surface splines [4] and one-dimensional numerical splines [5,6] were considered as alternatives for the pressure interpolations. Briefly, surface splines are based on the small deflection equation of an infinite plate and have a discontinuous second derivative at the input data points. One-dimensional cubic splines are based on the small deflection equation of an infinite beam and have a continuous second derivative and a discontinuous third derivative at the data input points. Surface splines are commonly used to interpolate elastic deflections of wings [7], but in the author's experience one-dimensional cubic splines have proved more reliable in the interpolation of pressure data and therefore have been used exclusively in this paper. One additional feature of cubic splines is that the first derivative (slope) of the interpolated curve is obtained as the evaluation of an analytical expression rather than by a numerical difference process, thereby reducing numerical errors in derivative calculations.

The interpolation procedures will be described using the Rectangular Supercritical Wing (RSW) of references 8 and 9 as an example since this wing was also used to generate the numerical results to be presented later. Figure 2 shows the analytical box layout for the RSW with the pressure measurement stations superimposed. The experimental data must be interpolated from the measurement stations to the quarter-chord pressure points at the midspan location of each of the analytical boxes. Figure 3 illustrates the interpolation process. First, the measured experimental data are spline fit chordwise at the experimental spanwise measurement stations (figure 3a) and interpolated to the chord stations used in the analytical model. The chordwise interpolated data are then spline fit spanwise and interpolated to the analytical span stations (figure 3b).

To avoid extrapolation of pressures in regions beyond the measurement stations of the RSW, the following techniques were used. At the trailing edge, additional "data points" were added which explicitly forced the pressure differential there to be zero. To avoid extrapolation on the inboard section, the pressure distribution was assumed to be symmetric from tip to tip for the purpose of determining the spline fits. Finally, to avoid problems at the outboard edge of the wing, the experimental data was divided by the factor $\sqrt{(1-\eta^2)}$ prior to spline fitting and interpolation. The actual values of the interpolated experimental pressures at each analytical span location were then recovered by multiplying the values of the interpolated modified pressures by the factor $\sqrt{(1-\eta^2)}$.

The above described interpolations are performed for steady data sets at different angles of attack and these data are then spline fit as a function of angle of attack. The analytical first derivative feature of one-dimensional cubic splines is then used to obtain the desired experimental lifting pressure coefficient derivative ΔC_{p_α} at the aerodynamic box locations.

The correction factors are just the ratios of the interpolated experimental and analytical pressure data at each box location (equation 1). This is illustrated in figure 4 which shows representative interpolated experimental pressure distributions and the uncorrected analytical pressure distributions for the RSW.

Correction factors can also be calculated which are applied to box downwashes instead of pressures if experimental downwash data are available. The experimental downwash for the RSW was not measured directly but could be calculated if both the airfoil shape and the deformation of the wing in the tunnel were known. The wing deformation of the RSW in the tunnel was not measured. Therefore, for this paper, a pseudo-experimental downwash distribution was determined using the analytical aerodynamic influence coefficient (AIC) matrix and the measured experimental pressure distribution. Equation 2 states the relationship between the box downwashes w and the pressure distribution ΔC_{p_α} in terms of the AIC matrix

$$\{w\} = [AIC]\left\{\Delta C_{p_\alpha}\right\} \tag{2}$$

The downwash correction factors are the ratios of the pseudo-experimental downwashes to the analytical downwashes as

$$\chi_w = \frac{w^e}{w^a} \tag{3}$$

Pressure corrections have the effect of modifying only the pressure on the box to which they are applied, whereas a downwash correction factor on one box affects the pressures on all other boxes to varying degrees through the AIC matrix. The effect of pressure correction factors on unsteady pressures is to modify the magnitude of the unsteady pressures. The only modification to phase is a shift of 180 degrees when the correction factor is negative. Downwash correction factors affect both the magnitude and phase of unsteady analytical pressure distributions. Applying either the pressure correction factors calculated from equation 1 or the downwash correction factors calculated by equation 3 achieve a complete match of steady analytical and experimental data.

Section Characteristics

A second approach to correction factor calculation involves matching one or more airfoil section properties, for example, lift and moment, (C_{ℓ_α} and C_{m_α}, respectively). If only one section property (ie. C_{ℓ_α} or C_{m_α}) needs to be matched, the pressure correction factor is simply the ratio of the experimental to the analytical section property for each airfoil section, for example

$$\chi_p = \frac{C^e_{\ell_\alpha}}{C^a_{\ell_\alpha}} \tag{4}$$

or

$$\chi_p = \frac{C^e_{m_\alpha}}{C^a_{m_\alpha}} \tag{5}$$

The same correction factor is applied to all the aerodynamic boxes along a chordwise strip at the span location for which the section characteristics are valid.

In most cases however, it is best to match both C_{ℓ_α} and C_{m_α} simultaneously. One way this can be accomplished is by using correction factors which vary linearly along the chord section as

$$\chi(\xi) = \chi'(\xi - \bar{\xi}) + \bar{\chi} \tag{6}$$

where χ' is the slope of the line and $\bar{\chi}$ is the value of the correction factor at the moment reference center. χ' and $\bar{\chi}$ are determined by solving the system of linear equations

$$\begin{Bmatrix} \bar{\chi} \\ \chi' \end{Bmatrix} = [A]^{-1} \begin{Bmatrix} C^e_{\ell_\alpha} \\ C^e_{m_\alpha}(\bar{\xi}) \end{Bmatrix} \tag{7}$$

where A is defined by

$$[A] = \begin{bmatrix} C^a_{\ell_\alpha} & C^a_{m_\alpha}(\bar{\xi}) \\ C^a_{m_\alpha}(\bar{\xi}) & \int_{\xi=0}^{\xi=1} \Delta C_{p_\alpha}(\xi)(\xi - \bar{\xi})^2 d\xi \end{bmatrix} \tag{8}$$

Experimental section C_{ℓ_α} can be calculated either by integrating ΔC_{p_α} along the chord using Gauss-Legendre Quadrature [10] for example, or as the derivative of the section lift with respect to angle of attack.

Alternatively, optimization techniques can be used to calculate correction factors which are different for each of the boxes along a chordwise strip. The correction factors for each strip are obtained as the design variables in an optimization problem where the objective is to minimize the square error in the desired section property (properties). For the i^{th} span station, the objective function is

$$J_i = \sum_{k=1}^{nf}\left(F_k - F_{D_k}\right)^2 \tag{9}$$

Because this approach matches section properties and not pressure distributions, the correction factors calculated by this method may result in an unrealistic analytical pressure distribution. This effect can be alleviated by 1) adding an additional term to the objective function for the i^{th} strip which minimizes the difference in the pressure distribution as

$$j_i = \sum_{k=1}^{nb_i} (1 - \chi_k)^2 \tag{10}$$

and/or 2) by including upper and lower bounds on the correction factors as inequality constraints in the optimization. For case 1), the total objective function to be minimized for each strip is

$$J_{tot_i} = J_i + Q_i j_i \tag{11}$$

where Q_i is an arbitrary weighting factor.

Instead of solving separate optimization problems for each strip, the correction factors for all the strips could be calculated simultaneously by summing the objective functions for each strip as

$$J_{tot} = \sum_{i=1}^{ns} J_{tot_i} \tag{12}$$

Total Forces

A third approach to correction factor calculation is to match total forces, total moments, or integrated pressures (eg. C_{L_α}, C_{M_α}, etc.). Figure 5 shows a bar chart comparing analytical force coefficients calculated using the Doublet Lattice Method (DLM) and the box layout of Figure 1 with experimental force data from reference 11 for the F/A-18. The goal of the methodology is to find a set of correction factors which improves the correlation of the analytical force results with known force data.

This methodology expands on the work of Giesing, Kalman, and Rodden[2] which uses a closed form solution of an optimization problem where total forces and moments are matched exactly using equality constraints and the objective function minimizes the variation of the modified pressure distribution from the original analysis. Correction factors are applied to either the aerodynamic box downwashes or pressures. The methodology described in this paper provides for more options in the formulation of the optimization problem, and uses numerical optimization rather than a closed form solution. This total force methodology is basically an extension of the section properties methodology described earlier.

The primary objective function for the total force matching problem is

$$J = \sum_{k=1}^{nf} \left(F_k - F_{D_k}\right)^2 \tag{13}$$

where the summation is over the total number of forces to be matched (C_{L_α}, C_{M_α}, C_{L_δ}, etc). As in the previous method, changes in the pressure distribution can be minimized by appending a term

$$j = \sum_{k=1}^{nb} \left(1 - \chi_k\right)^2 \tag{14}$$

to equation 13, where nb here is the total number of boxes, or by implementing inequality constraints which provide upper and lower bounds on the correction factors. Additionally, inequality constraints on individual forces can be formulated as

$$g_k \le \frac{\left(\dfrac{F_k - F_{D_k}}{F_{D_k}}\right)^2}{E^2} - 1 \tag{15}$$

in order to improve the matching of specific forces.

Numerical optimization to calculate the correction factors to match total forces or section properties can be achieved using numerical optimization techniques, such as those which are available in the Automated Design Synthesis (ADS)[12] nonlinear programming software package.

Results

The pressure distribution matching method for correction factor calculation has been implemented and results for this methodology will be presented in this paper. The results are for a Rectangular Supercritical Wing (RSW) that was tested in the NASA Langley Research Center Transonic Dynamics Tunnel. Reference 8 presents the geometric and structural properties of the RSW and reference 9 gives tabular listings of steady pressure data for a range of Mach numbers and angles of attack, and unsteady oscillatory experimental pressure data for a range of Mach numbers, reduced frequencies and mean angles of attack. Figure 2, mentioned earlier, shows the aerodynamic box layout used in the analysis to calculate the analytical pressures. Superimposed are the locations at which experimental steady and unsteady pressure data were measured. Steady experimental data were interpolated from the measurement stations to the analytical locations as described in the methodology section of the paper in order for pressure and downwash correction factors to be calculated. Unsteady measured data were also interpolated to analytical locations in order that direct comparisons could be made between the experimental pressures and the uncorrected and corrected analytical pressures.

Figure 6 shows a typical chordwise distribution of steady upper surface, lower surface, and lifting pressures at Mach 0.4, showing the distribution of pressures on this supercritical wing. Note the high lift on the rear half of the airfoil where supercritical wings typically have high camber. Figure 7 shows the effects of angle-of-attack variation on the lifting pressure distribution, with chordwise distributions at midspan shown in figure 7a and spanwise distributions at midchord shown in figure 7b. The derivatives of these lifting pressures with respect to angle of attack are the quantities which are to be matched in this analysis. Figure 4 shows a typical comparison of experimental and analytical steady ΔC_{p_α} distributions from which pressure correction factors are calculated. Note that the pressures are underpredicted by the DLM toward the leading edge and reasonably well predicted toward the trailing edge.

Figure 8 shows pressure correction factors (χ_p) that were calculated from steady pressure data at a Mach number of 0.4 for the RSW. The chordwise distributions at several span stations and the spanwise distributions at several chord locations are provided to give an overall view of the behavior of the correction factors over the surface. Note that the pressure correction factors towards the trailing edge of the supercritical airfoil increase. This is basically due to the low magnitudes of the pressures in this region, where the ratio of the experimental to analytical pressures can be large even though the actual pressure prediction error is small. The figures also show that the correction factors can be negative as occured toward the outboard edge of the wing at about the mid- to three-quarter chord location. This may be due to variations in the flow around the wing tip caused by the unconventional chordwise pressure distribution over a supercritical wing, as illustrated in Figure 6. This unconventional flow around the wing tip is not represented by the Doublet Lattice Method. Figure 9 shows the downwash correction factors (χ_W) which were calculated to match the steady experimental data for the same test condition as figure 8. Applying either the pressure or downwash correction factors results in a match between the analytical and experimental steady pressure distributions.

Unsteady analytical pressures were calculated using the Doublet Lattice Method to obtain oscillatory aerodynamics at reduced frequencies corresponding to points where unsteady wind tunnel pressure data were available. These calculations were conducted so that direct comparisons could be made between the unsteady experimental pressure data and corrected and uncorrected analytical calculations. Figure 10 shows a comparison of unsteady experimental pressure data (magnitude and phase) and uncorrected and corrected analytical data for two reduced frequencies at Mach 0.4. The purpose of this comparison was to determine whether the correction factors based on steady data will improve unsteady pressure calculations over a reduced frequency range. Figures 10a and 10b compare the magnitudes of the unsteady pressures at a span station of η=.525 for reduced frequencies of 0.309 (10 Hertz oscillation), and 0.618 (20 Hertz oscillation). The corresponding phases are shown in Figures 10c and 10d. Both downwash and pressure correction factors resulted in improved prediction of the pressure magnitudes on the leading edge of the airfoil, with mixed results farther aft where the magnitudes are much smaller. The effect of downwash correction factors on phase is generally beneficial, with poorer results in the same regions as for the pressure magnitudes.

Correction factors based on steady pressure data were calculated for four Mach numbers ranging from 0.266 to 0.8. The pressure correction factors are shown in Figure 11 and the downwash correction factors are shown in Figure 12. This analysis was conducted to determine if correction factors calculated to match pressure data at one Mach number might be applicable over a Mach number range. As shown, both sets of correction factors vary with Mach number, indicating that for the RSW, a single set of correction factors calculated at one Mach number is not adequate over a wide range of Mach numbers.

Figure 13 shows the unsteady pressure magnitudes for Mach numbers 0.266, 0.7, and 0.8 for an oscillation frequency of 10 Hertz, and figure 10a shows the corresponding data for Mach 0.4. Figures 14 and 10c show the phase of the unsteady pressures for the same test conditions. It is noted that the test medium for Mach 0.266 was air while the test medium for the other Mach numbers was freon. Although the reduced frequencies are not constant as they should be to isolate a Mach number effect, the reduced frequencies for Mach numbers 0.266, 0.7 and 0.8 do not vary widely, so that the trends in Figures 13 and 14 can be attributed mostly to Mach number effects. Both types of correction factors, downwash and pressure, result in improved leading edge matching of the pressure magnitudes, including the transonic(shock) effects at Mach 0.8. This result is similar to that shown by Pitt[3]. The downwash correction factors also provided some improvement in the phase distributions.

Concluding Remarks

Three methods of correction factor calculation have been developed to match surface pressure distributions, to match section properties, and to match total forces, moments and control derivatives. Pressure and downwash correction factors to match surface pressure distributions have been calculated based on steady experimental data for a range of Mach numbers for a rectangular supercritical wing. Uncorrected and corrected analytical pressure data have been calculated and compared with steady and unsteady experimental pressure data at a range of Mach numbers and reduced frequencies. Correction factors are shown to improve the analytical calculation of unsteady pressures and could be used to modify analytical pressure calculations to account for some nonlinear aerodynamic effects.

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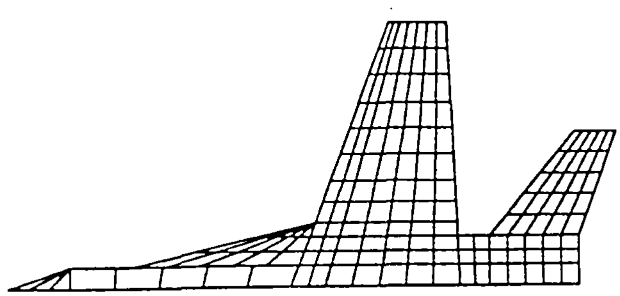

Figure 1. Typical aerodynamic box layout for Doublet Lattice Method.

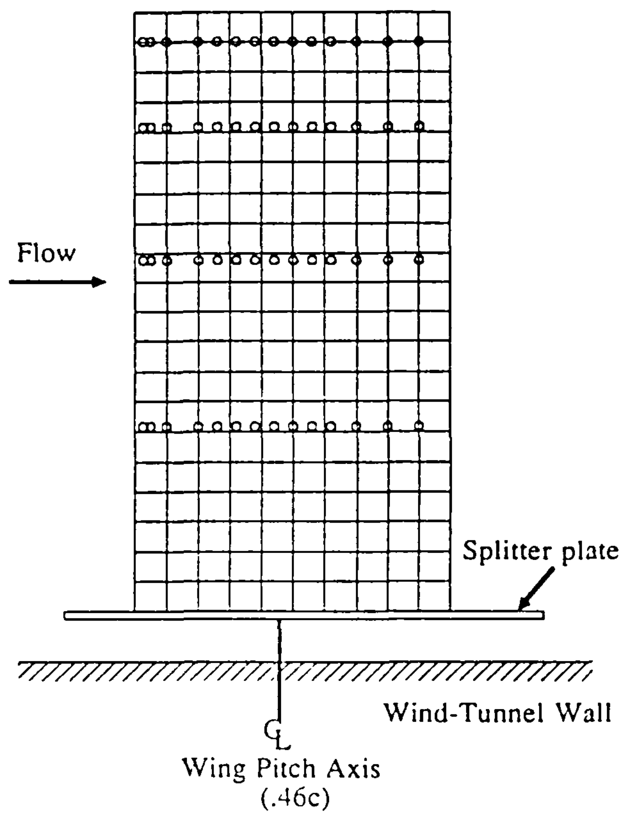

Figure 2. Analytical box layout with experimental pressure measurement stations of Rectangular Supercritical Wing.

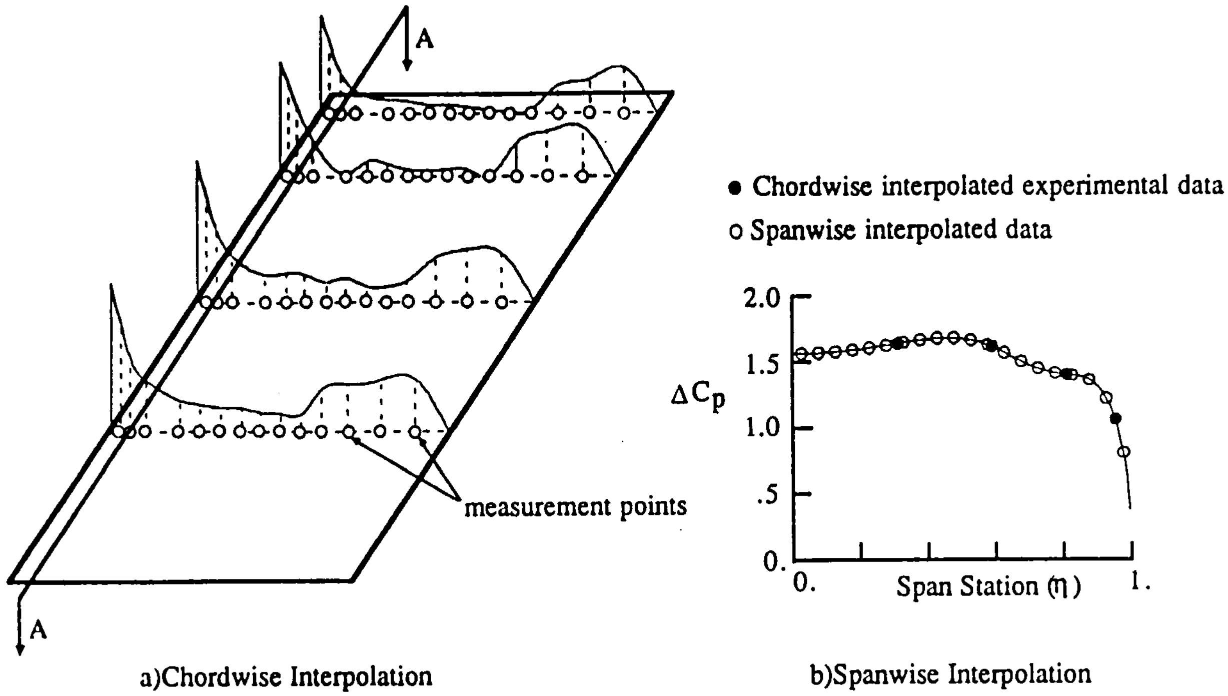

Figure 3. Interpolation of experimental lifting pressures to analytical locations.

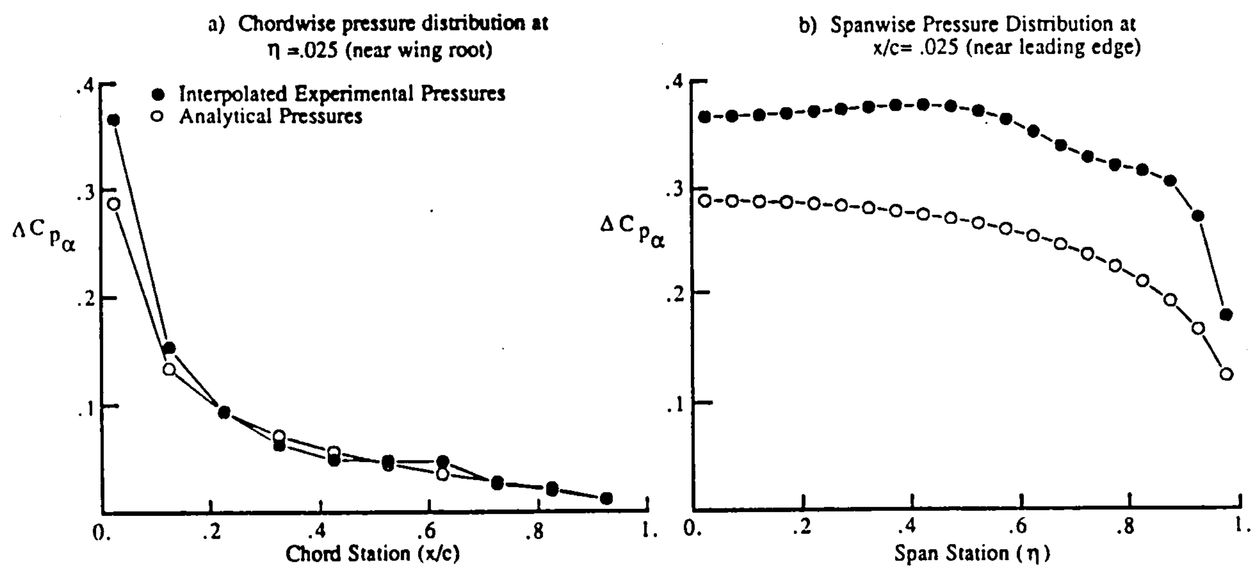

Figure 4. Comparison of steady experimental and analytical steady pressure distributions to calculate correction factors.

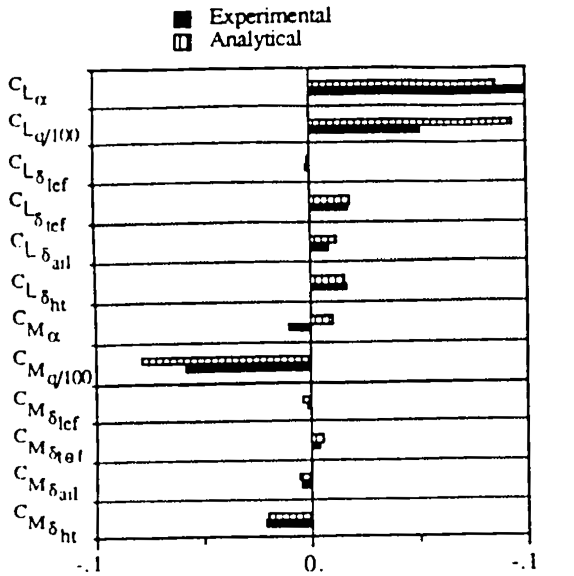

Figure 5. Comparison of F-18 total force coefficients (M=0.8).

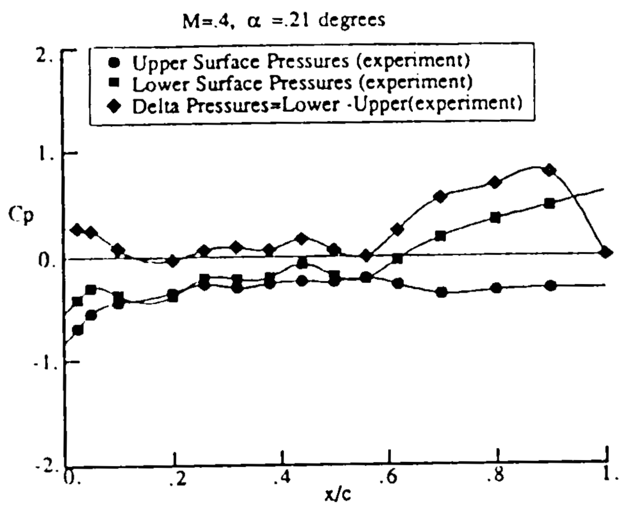

Figure 6. Typical chordwise distribution of upper, lower and differential pressure distributions for RSW.

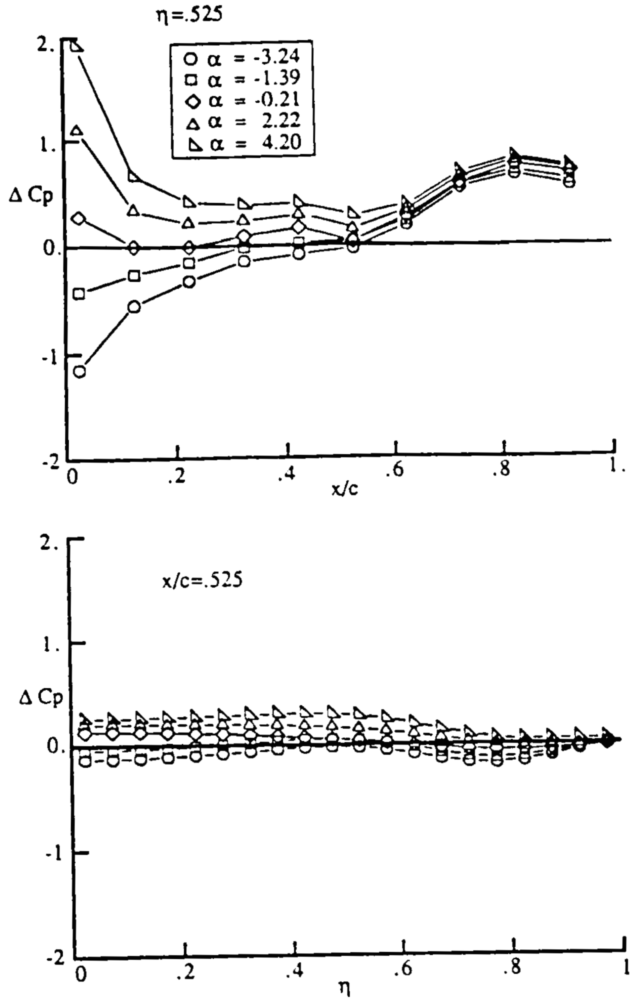

Figure 7. Effect of angle of attack on steady lifting pressure distribution of RSW (M=0.4).

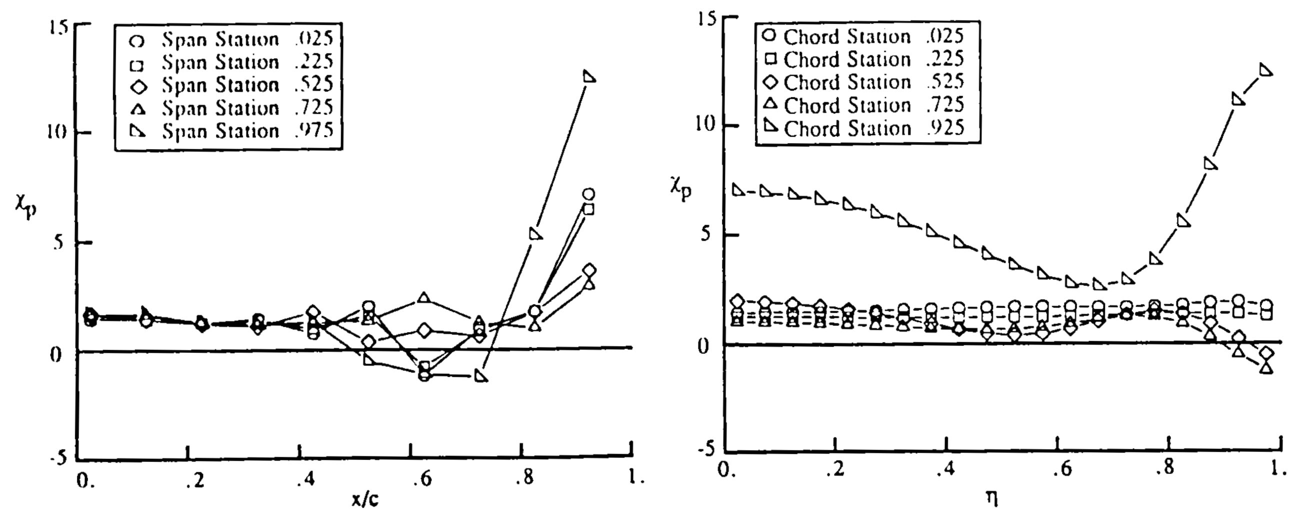

Figure 8. Pressure correction factors for RSW at M=0.4.

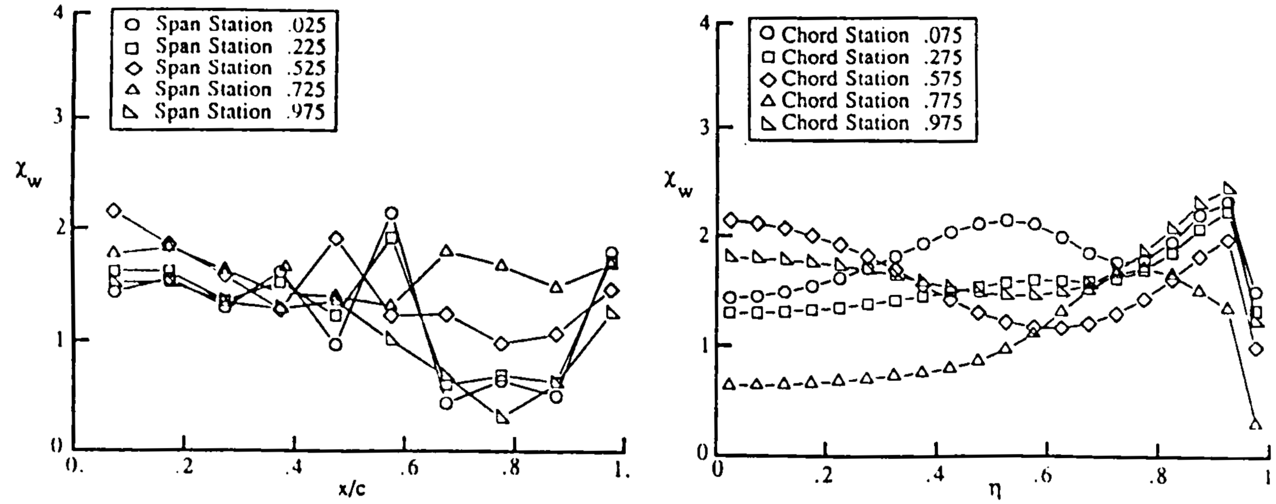

Figure 9. Downwash correction factors for RSW at M=0.4.

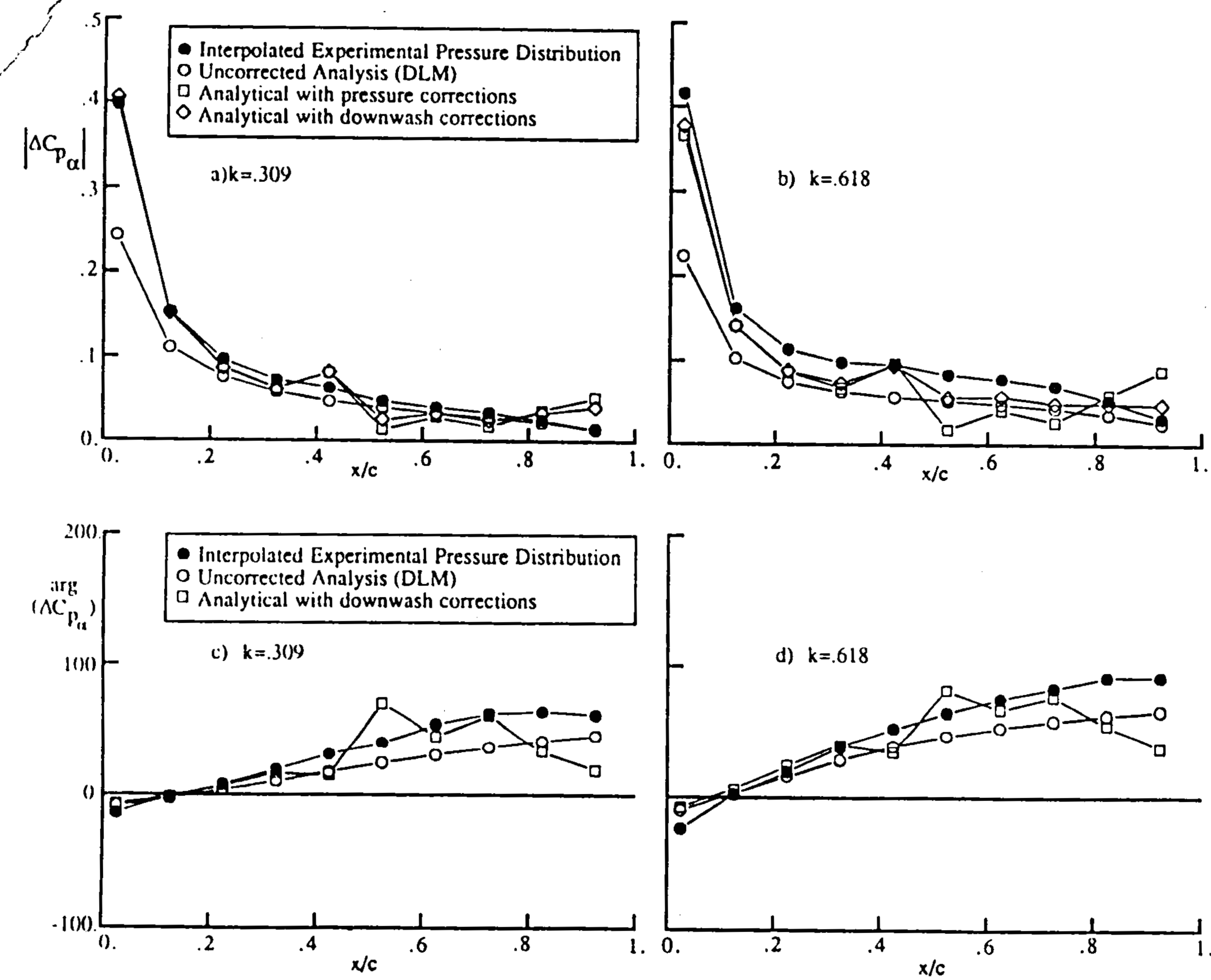

Figure 10. Effect of oscillation frequency on unsteady ΔC_{p_α}.

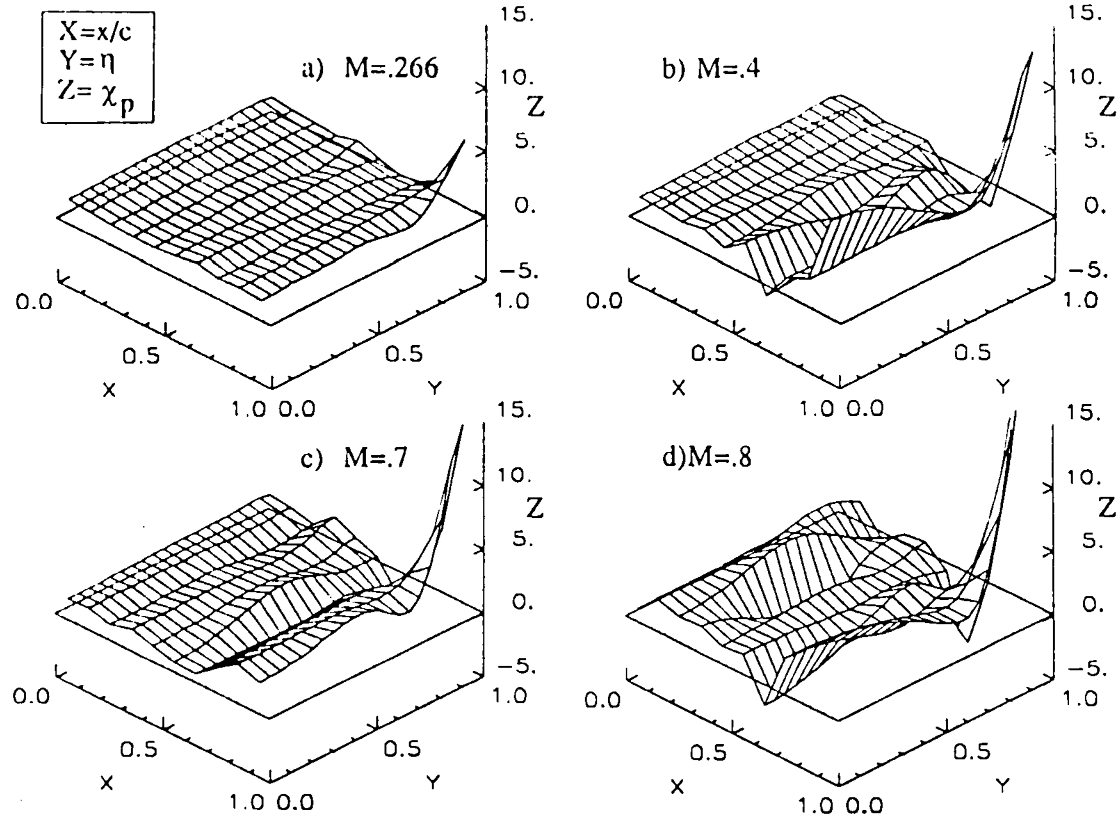

Figure 11. Variation of pressure correction factors with Mach number.

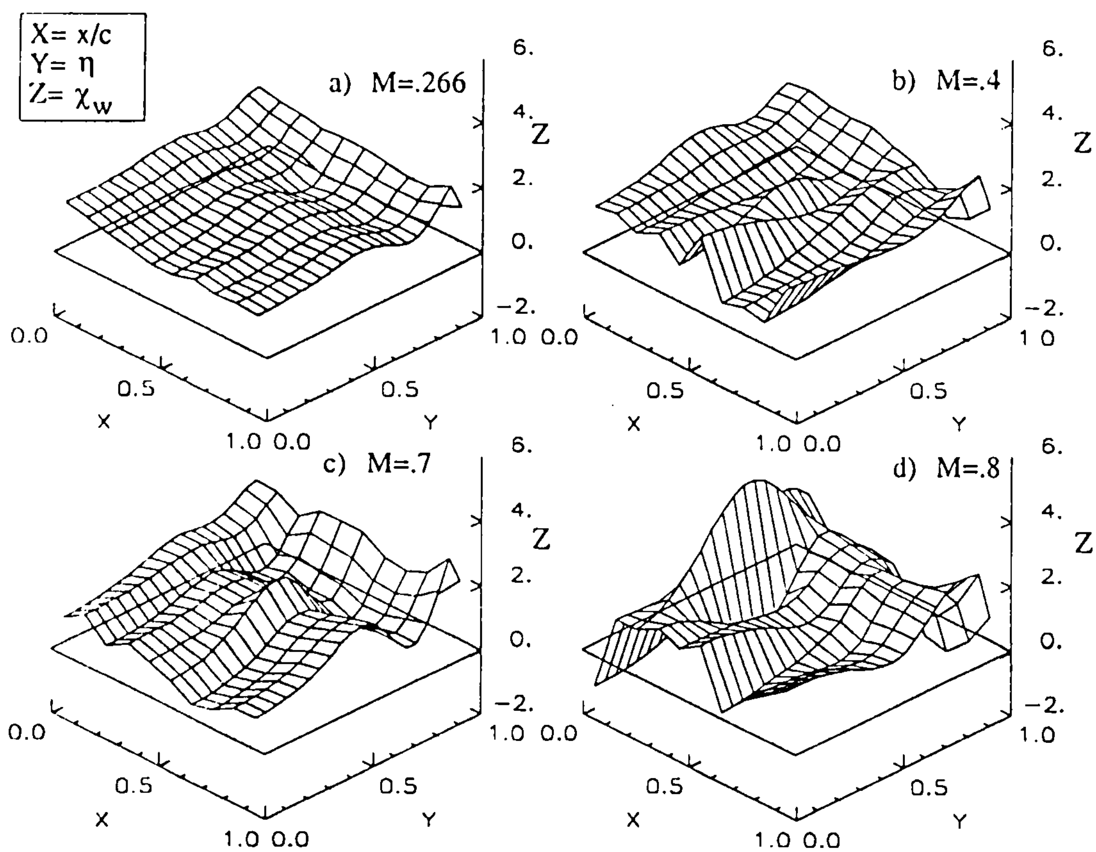

Figure 12. Variation of downwash correction factors with Mach number.

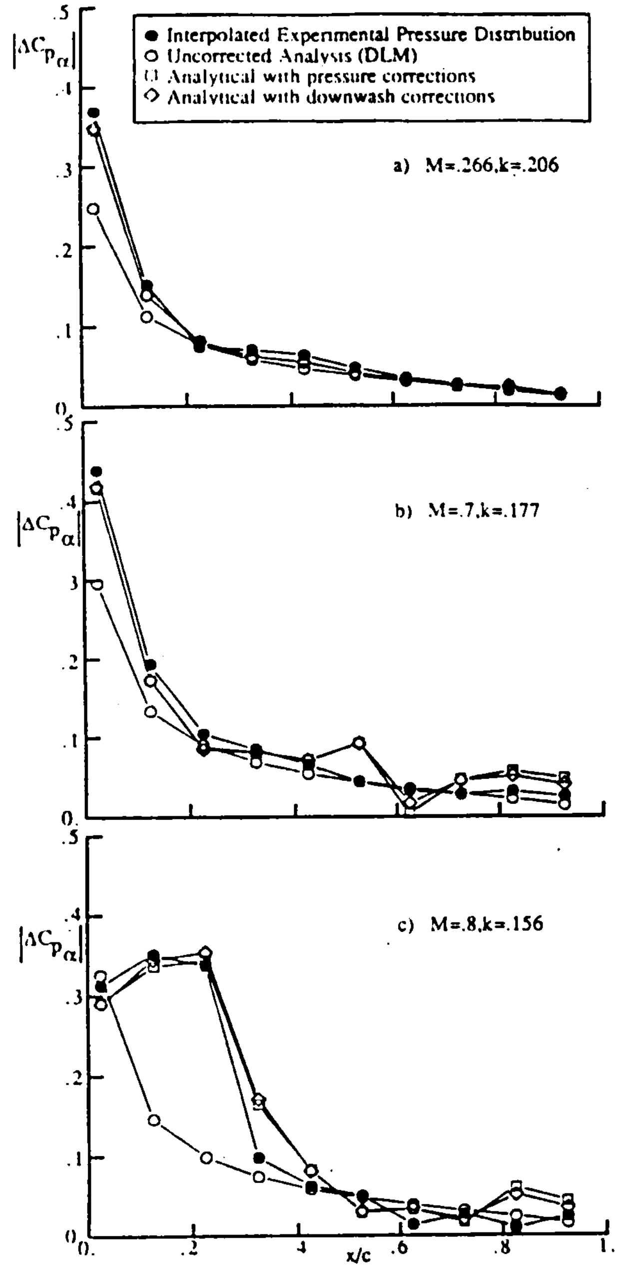

Figure 13. Comparisons of uncorrected and corrected magnitude of ΔC_{p_α} for Mach numbers 0.266-0.8.

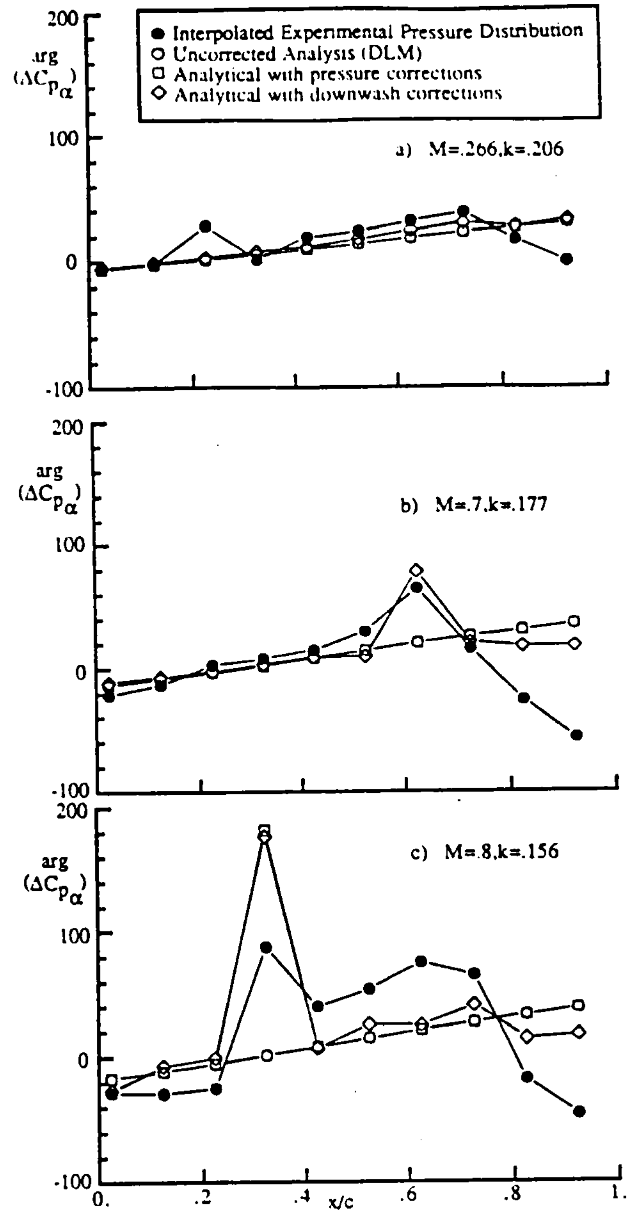

Figure 14. Comparisons of uncorrected and corrected phase of ΔC_{p_α} for Mach numbers 0.266-0.8.

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16. Abstract

Correction factor methodologies have been developed which use steady experimental or analytical pressure or force data to correct steady and unsteady aerodynamic calculations. Three methods of calculating correction factors have been developed to match steady surface pressure distributions, to match airfoil section forces and moments, and to match total forces and moments. Data for a rectangular supercritical wing that was previously tested in the NASA Langley Research Center Transonic Dynamics Tunnel have been used to determine correction factors to match surface pressure distributions for a range of Mach numbers. These correction factors have also been applied to unsteady aerodynamic calculations and comparisons have been made with oscillatory experimental data for a range of reduced frequencies at several Mach numbers.

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