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Improving CAP–TSD Steady Pressure Solutions through Airfoil Slope Modification

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Abstract

A modification of airfoil section geometry is examined for improvement of the leading edge pressures predicted by the Computational Aeroelasticity Program—Transonic Small Disturbance (CAP–TSD) [1]. Results are compared with Eppler solutions [2, 3] to assess improvement.

Preliminary results indicate that a fading function modification of section slopes is capable of significant improvements in the pressures near the leading edge computed by CAP–TSD. Application of this modification to airfoil geometry before use in CAP–TSD is shown to reduce the nonphysical pressure peak predicted by the transonic small disturbance solver. A second advantage of the slope modification is the substantial reduction in sensitivity of CAP–TSD steady pressure solutions to the computational mesh.

Introduction

The Computational Aeroelasticity Program—Transonic Small Disturbance (CAP–TSD) code is an algorithm developed to predict unsteady behavior of realistic aircraft configurations [1]. CAP–TSD makes use of the Transonic Small Disturbance equation to solve for the steady and unsteady pressures acting on the aircraft geometry. This equation assumes that the geometry produces only a small disturbance of the flow, restricting the input geometry to thin wings at small angles of attack.

Applying the Transonic Small Disturbance equation to thick wing geometries violates the small disturbance assumption and results in large values of pressure near the leading edge that are nonphysical in nature. These large pressure values reduce the accuracy of CAP–TSD flutter analyses and reveals the sensitivity of CAP–TSD solutions to the computational mesh density.

The primary objective of the current study is to develop an empirical method to reduce the magnitude of the nonphysical pressures near the leading edge. A secondary objective is to reduce the mesh sensitivity of CAP–TSD steady pressure solutions.

Transonic Small Disturbance Equation

The Transonic Small Disturbance equation used in CAP–TSD is represented by

$$\frac{\partial f_0}{\partial t}+\frac{\partial f_1}{\partial x}+\frac{\partial f_2}{\partial y}+\frac{\partial f_3}{\partial z}=0 \tag{1}$$

where,

$$f_0=-A\phi_t-B\phi_x \tag{2}$$

$$f_1=E\phi_x+F\phi_x^2+G\phi_y^2 \tag{3}$$

$$f_2=\phi_y+H\phi_x\phi_y \tag{4}$$

$$f_3=\phi_z \tag{5}$$

$$A=M_\infty^2 \qquad B=2M_\infty^2 \qquad E=1-M_\infty^2 \tag{6}$$

and the coefficients are defined as,

$$F=\frac{-1}{2}(\gamma+1)M_\infty^2 \tag{7}$$

$$G=\frac{1}{2}(\gamma-3)M_\infty^2 \tag{8}$$

$$H=-(\gamma-1)M_\infty^2\ . \tag{9}$$

In equations (1–9) the ϕ term is the small disturbance velocity potential, M_∞ is the free–stream Mach number, and γ is the specific heat ratio. The Transonic Small Disturbance (TSD) equation is used by CAP–TSD to produce steady or unsteady pressure solutions. Steady solutions are the focus of the present study. The TSD equation assumes that the wing geometry causes only a small disturbance of the flow. Applying the TSD equation to thick wing geometries violates the small disturbance assumption and results in the prediction of a pressure spike near the leading edge that is nonphysical in nature. This leading edge pressure spike is predicted because of the overestimation of surface velocities near the leading edge.

According to the equations employed in CAP–TSD, surface slopes of the wing geometry define the z–component of the perturbation velocity, ϕ_Z. This leads to an inconsistency between the computational scheme and the physics of the problem. As the computational mesh is refined near the leading edge, increasing slopes increase the magnitude of the ϕ_Z term. This leads to the prediction of a significant ϕ_Z term at the stagnation point of the section. It is this inconsistency between the physics and the computational treatment of the problem that gives rise to the leading edge pressure spike.

Method of Approach

The current work examines slope modifications applied to two different 2–D airfoil sections, the MS–0313 [4] and NLR–7301 [5]. A cosine distribution of points with no point at the leading edge of the section was used to generate the computational meshes applied to these airfoil sections. In these grids, as the number of grid points was increased, the first point of the mesh is successively closer to the leading edge of the section.

The slope modifications used in this investigation are based on Riegel's Rule as discussed by Van Dyke [6]. Riegel's Rule is a first–order velocity correction for use with thin airfoil theory solutions for surface speed. Riegel's Rule is represented by

$$q/U \;=\; \mathit{q/U} \cos h \tag{10}$$

where,

$$h = \tan^{-1}(dz/dx)\,. \tag{11}$$

In equations (10) and (11), q/U is the corrected surface speed, *q/U* is the original surface speed, and dz/dx is the section slope.

Riegel's Rule is used as the basis for the slope modifications because the nonphysical pressure spike of CAP–TSD solutions is similar in appearance to the pressure spike of thin airfoil theory solutions. As discussed in the previous section, the perturbation velocity is used by the Transonic Small Disturbance equation to solve for the steady pressure coefficients, and the predicted surface speeds are driven by section slopes. The slope modification based on Riegel's Rule is represented by

$$dz/dx = \mathit{dz/dx} \cos h \tag{12}$$

where, dz/dx is the modified section slope, *dz/dx* is the original section slope, and h is given in equation (11). The advantage of applying equation (12) to the section geometry before use in CAP–TSD is that the slopes are significantly reduced, resulting in a section geometry in better agreement with the small disturbance assumption. The negative aspect of this geometry modification is that the section geometry input to CAP–TSD may be significantly different than that of the original section. For this reason a second slope modification is examined which alters only a portion of the section near the leading edge.

The nonphysical pressure spike is only evident near the leading edge of the section. For this reason a slope modification which only alters the leading edge geometry is investigated. A slope modification similar to that of equation (12) is applied with a fading function, such that the leading edge is gradually altered up to 10% chord. From 10% chord aft the section geometry is unaltered. The fading slope modification is represented by

$$dz/dx = \mathit{dz/dx}\,[\,1 + (\,f\cos(h) - 1\,)\cos(\,\pi\, x_{pt} / 2(e_{pt})\,] \qquad (13)$$

where, dz/dx is the modified slope, *dz/dx* is the true section slope, f is the function constant (altered to match desired pressure coefficients), x_{pt} is the grid point number of the point considered, and e_{pt} is the grid point number corresponding to the end point of the fade. For the purposes of the current investigation the grid point number corresponding to 10% chord is chosen for e_{pt}.

Comparison with Eppler

The current investigation requires a full–potential solution to assess the accuracy of the CAP–TSD solutions. The Eppler computational algorithm [2, 3] is used to produce this solution. Eppler is a potential flow solver which makes use of a panel method and compressibility correction to predict steady pressure coefficients on a given airfoil.

The full–potential equation is a higher–level approximation than the transonic small disturbance equation. It does not assume a small disturbance but still assumes isentropic, irrotational, and inviscid flow. Although a full–potential solver such as FLO36, developed by Jameson [7], would be most appropriate, Eppler is used for the current investigation because of accessibility and computational time considerations. Figure 1 shows a comparison of steady pressure coefficients as predicted by Eppler and FLO36

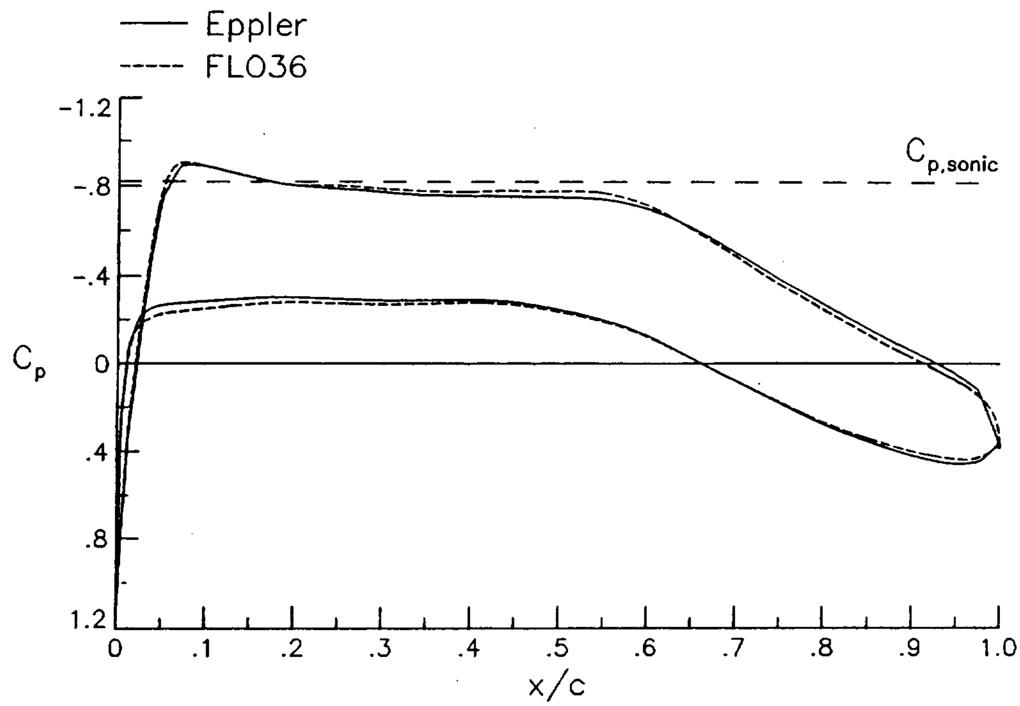

Figure 1: Comparison of Eppler and FLO36 Pressure Solutions for MS–0313 airfoil section, M= 0.69, alpha=–0.75 deg

for the MS–0313 airfoil section at a Mach number of 0.69 and angle of attack of –0.75°. Figure 1 reveals a good comparison between Eppler and FLO36 for the condition examined. This comparison is the basis of justification for using the Eppler code. A limitation of using Eppler for this investigation is that the computational code is not capable of solving for flows in the transonic range. For this reason the Mach numbers examined must be below those which produce sonic flow. Although figure 1 shows a slight violation of this requirement, subsequent analyses were maintained below the sonic flow level.

Discussion of Results

Figures 2, 3, and 4 display the leading edge pressure rise present in CAP–TSD solutions for unaltered airfoil geometry, Riegel's Rule modified slope geometry, and fading function modified slope geometry, respectively. Comparison of these three figures lends insight into the level of improvement the slope modifications are capable of. Figure 2 displays the characteristic pressure spike resulting from a CAP–TSD solution for the NLR–7301 airfoil geometry.

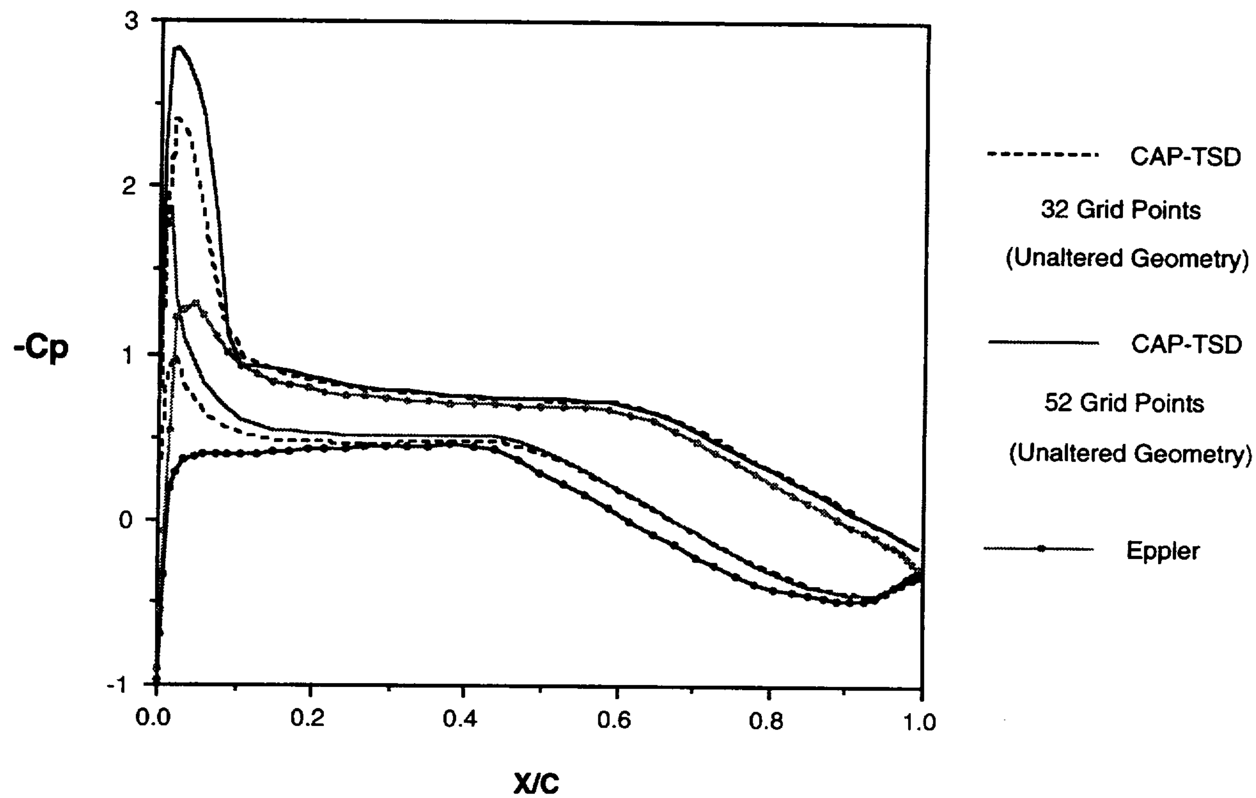

Figure 2: Comparison of CAP–TSD and Eppler Solutions for Thick Section Geometry

The solutions shown in figure 2 are for the NLR–7301 section at a Mach number of 0.6 and angle of attack of 0^o. Note that the pressure spike becomes increasingly severe as the number of computational mesh points is increased from 32 to 52. This is because the first grid point of the 52–point case is nearer the leading edge of the section, and therefore has an increased slope over that of the 32–point case. Another key point of figure 2 is the severity of the pressure spike in both CAP–TSD solutions compared to the physical leading edge pressure rise indicated by the Eppler solution. The primary objective of the two airfoil slope modifications is to reduce the severity of the pressure spike predicted by CAP–TSD.

Figure 3 shows the effectiveness of applying the Riegel's Rule slope modification to the NLR–7301 section geometry prior to use in CAP–TSD. The Riegel's Rule modification is presented in equations (11) and (12).

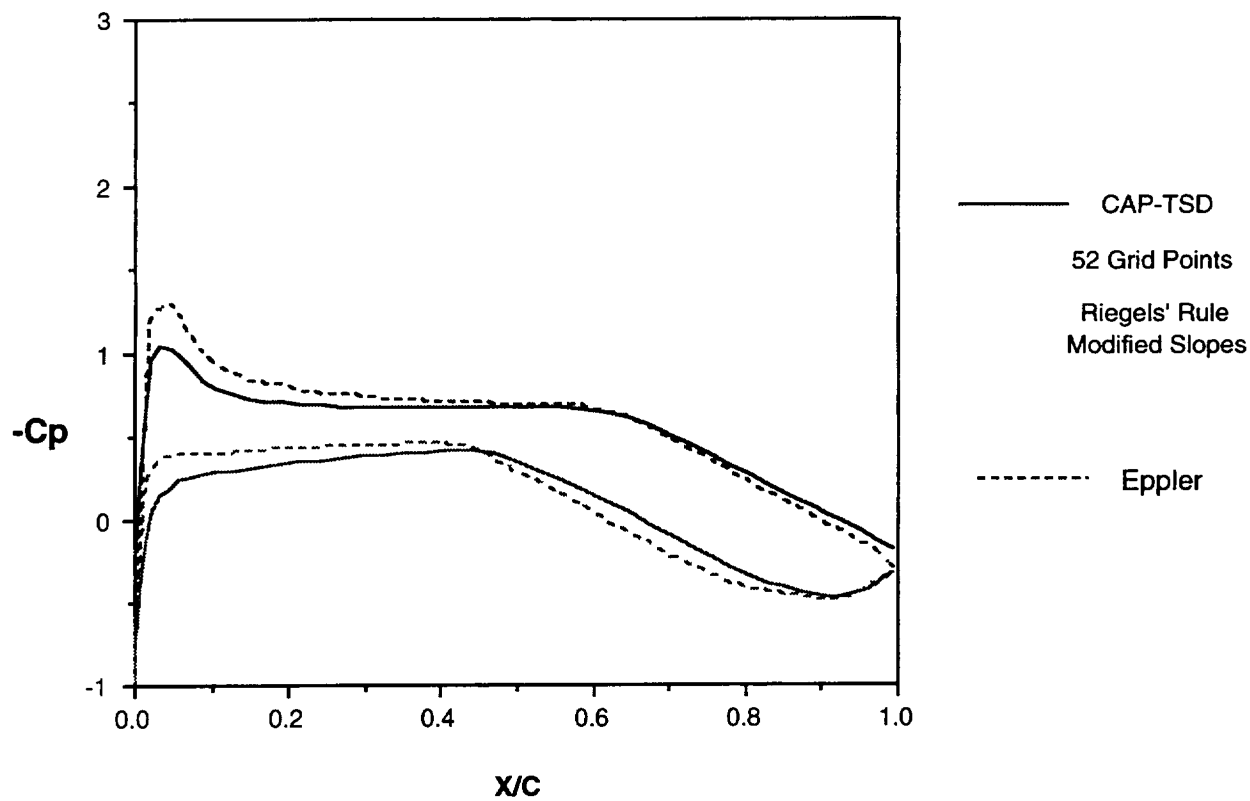

Figure 3: Comparison of CAP–TSD Solution for Modified Section Geometry with the Eppler Solution

The solutions in figure 3 correspond to the conditions used for the 52–grid–point solution in figure 2, with a Mach number of 0.6 and 0^{o} angle of attack. The scale of the axes in figures 2 and 3 is the same. This scaling allows the Riegel's Rule slope modified solution of figure 3 to be easily compared with the solution for the unaltered section geometry displayed in figure 2. Figure 3 reveals that the Riegel's Rule slope modification over–corrects the nonphysical leading edge pressure spike such that the CAP–TSD solution under predicts the Eppler solution. The slope modification results in a significant improvement in the pressure coefficients near the leading edge. The upper surface pressure spike of the Riegel's Rule slope modification has a peak coefficient of –1.0 compared to the peak coefficient of –2.8 for the CAP–TSD solution of the unaltered section geometry. The Eppler solution has an upper surface pressure coefficient of –1.3 at the leading edge pressure peak. This corresponds to a 119.0% difference between Eppler and the CAP–TSD unaltered geometry solution compared to a 23% difference between Eppler and the slope modified CAP–TSD solution.

Figure 4 displays the effectiveness of applying the fading modified slope geometry to CAP–TSD.

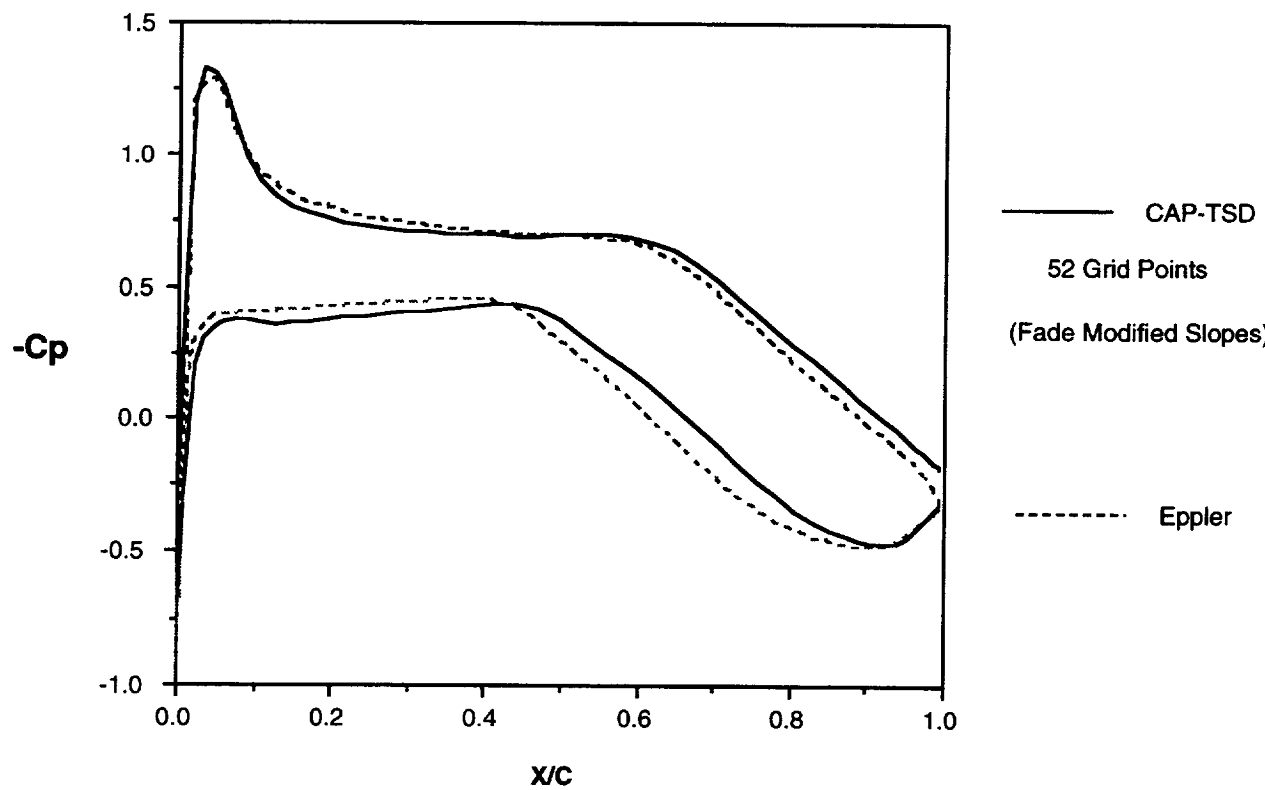

Figure 4: Comparison of CAP–TSD Solution for Fading Slope Modified Section Geometry and Eppler

Conditions for the solutions displayed in figure 4 correspond to those of figures 2 and 3, that is, a 52–grid point computational mesh, a Mach number of 0.6, and an angle of attack of 0°.
Note that in figure 4 the y–axis range is altered from that of figures 2 and 3. This change allows an improved view of the level to which the CAP–TSD solution using the fading modified slopes

agrees with the Eppler solution. The fading slope modification is presented in equations (11) and (13). The results of using the fading slope modification is shown in figure 4, and it is seen to significantly improve the correspondence between CAP–TSD and Eppler solutions.
The leading edge peak of the upper surface pressure corresponds to a coefficient of -1.3 for the CAP–TSD solution with fading function modified slopes. This corresponds to a percentage difference of 2.4% between the Eppler solution and the CAP–TSD solution using the fading modified slope geometry.

One advantage of the fading modification over Riegel's Rule is that only the leading edge of the section is altered. This leaves the section's less severe slopes lying behind the leading 10% chord unaltered. This way the modification places greater emphasis on the leading edge region and de–emphasizes the aft–portion of the airfoil, where the true section geometry may be assumed to be more consistent with the small disturbance assumption.

The fading slope modification makes use of a constant (fade factor) to improve correspondence between the CAP–TSD and the target solutions. This factor is represented as f in equation (13). The factor used for the results displayed in figure 4 is 1.2. For best results the factor must be chosen through comparison of CAP–TSD and the "ideal" solution. This requires that the target solution be known before use of the fading slope modification. Figures 5–9 will provide insight into the degree to which the fade factor, f, depends on angle of attack, Mach number, and leading edge geometry.

Figure 5 displays a comparison of the CAP–TSD solutions for both the unaltered and fading modified slope geometries.

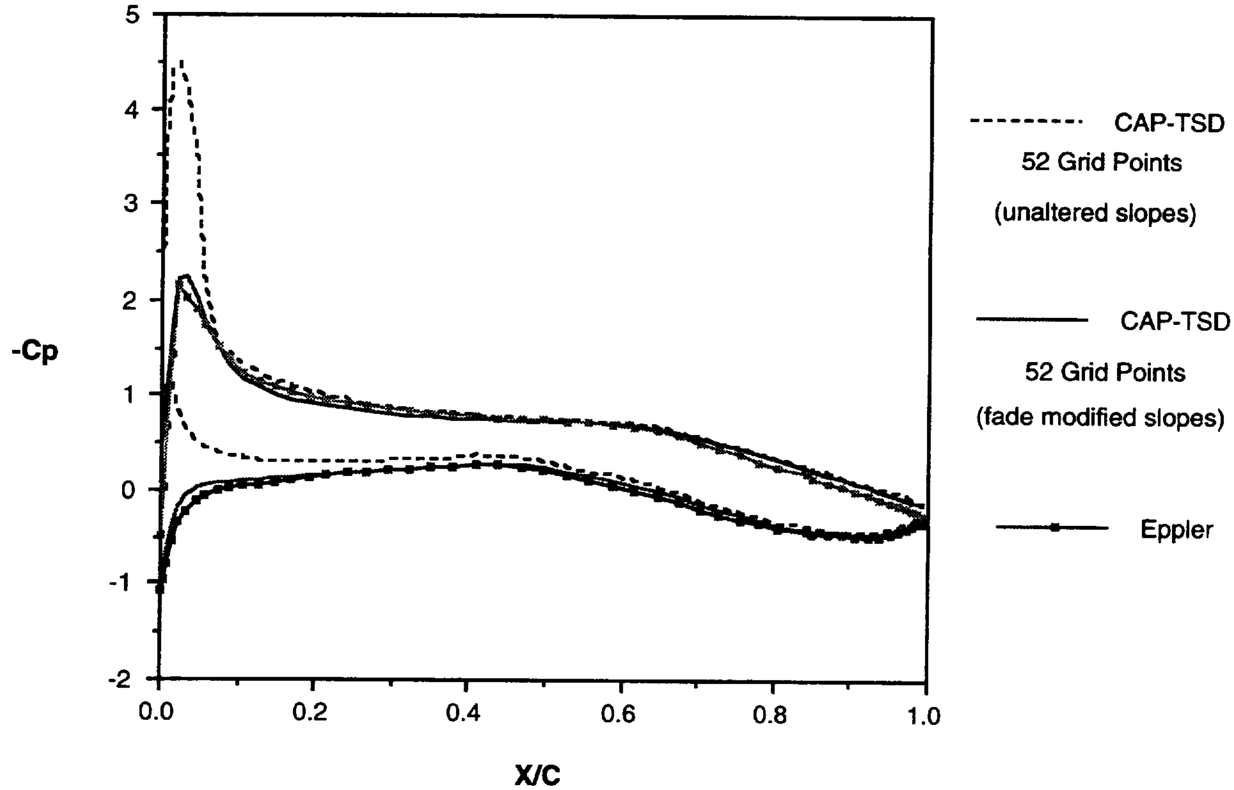

Figure 5: Comparison of Eppler Solution with CAP–TSD Solutions for Fading Modified and Unaltered Section Slopes NLR–7301 Airfoil, Mach = 0.5, $\alpha = 2^o$

Solutions displayed in figure 5 are for the NLR–7301 section with Mach number equal to 0.5, angle of attack of 2^o, and a 52–point computational mesh. The fade factor, f, is 1.2. This figure shows that the fading slope modification yields a CAP–TSD solution that is in good agreement with the Eppler solution. Figure 5, also shows that the combined changes of angle of attack and Mach number from those used for the solutions displayed in figure 4 have little effect on the choice of fade factor. A factor of 1.2 appears to be appropriate for both cases.

Figure 6 displays the CAP–TSD and Eppler solutions for the MS–0313 airfoil section with the conditions of a Mach number equal to 0.69 and angle of attack of -0.75^o.

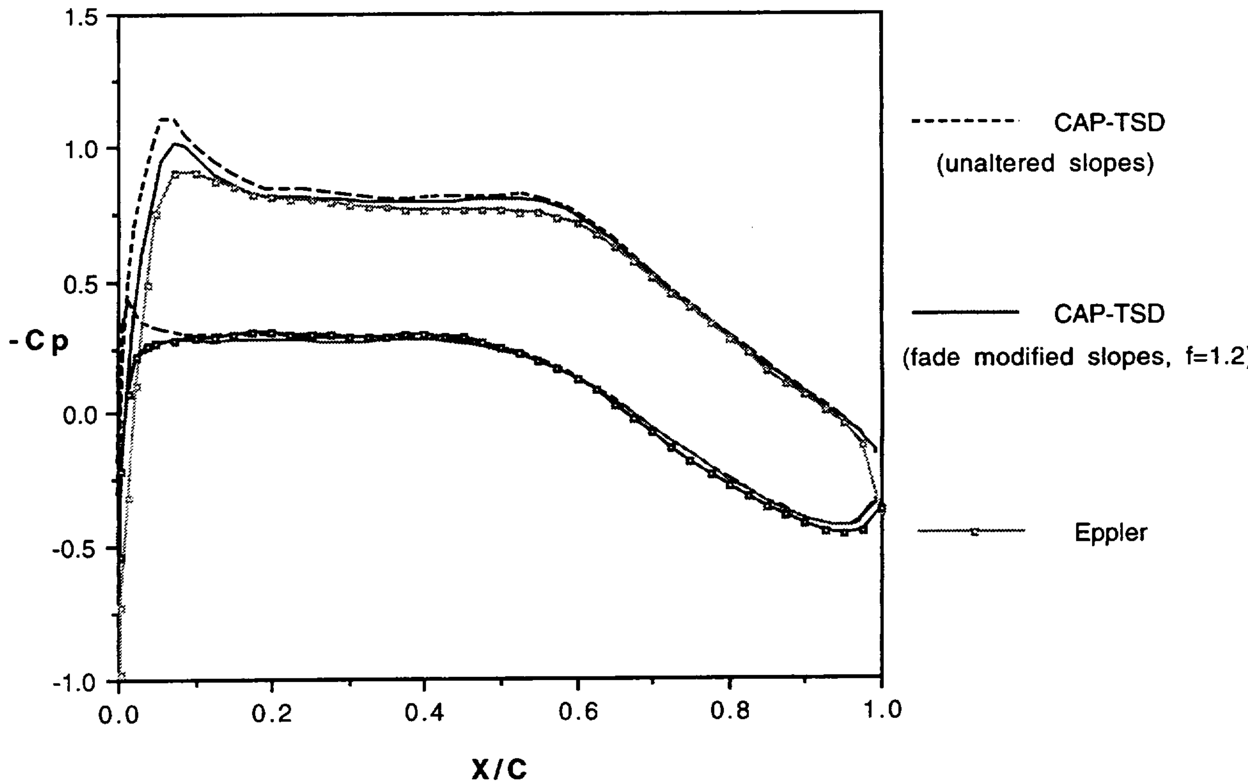

Figure 6: Comparison of CAP–TSD (Fade and Unaltered Geometries) and Eppler Solutions for MS–0313 Airfoil Section
Mach = 0.69, $\alpha = -0.75^{o}$

The conditions of the solutions displayed in figure 6 are identical to those of figure 1, the comparison of Eppler and the Full Potential solver FLO36. The fading slope modified solution displayed in figure 6 uses a fade factor, f, of 1.2. This comparison shows that the thinner leading edge slopes of the MS–0313 section allow CAP–TSD to produce a solution in better agreement with Eppler than for the NLR–7301. Note that the fading slope modification slightly improves the CAP–TSD solution in comparison with the unaltered geometry solution. Though an improvement, the fading slope modification does not produce a CAP–TSD solution at the level of agreement with Eppler displayed in the previous figures. This indicates that the fade factor of 1.2 is too high a value for the MS–0313 section at this Mach number and angle of attack.

Figure 7 displays a comparison of CAP–TSD and Eppler solutions for the same conditions of figure 6, a Mach number of 0.69, angle of attack of –0.75°, and 52–point computational mesh. The fade factor of the fading slope modification is here changed from 1.2 to 1.0.

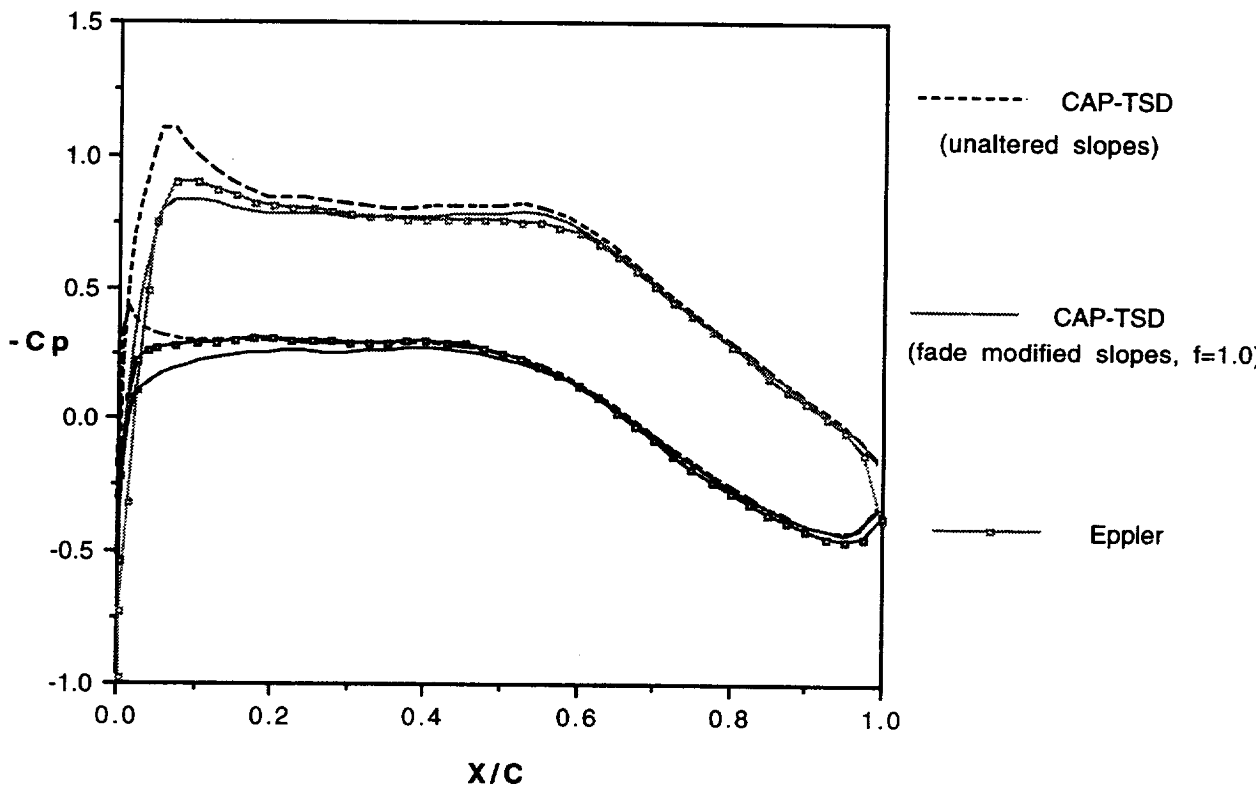

Figure 7: Comparison of CAP–TSD and Eppler Solutions for MS–0313 Airfoil Section, Mach = 0.69, α = –.75°

Figure 7 shows that for these conditions and the MS–0313 section a fade factor of 1.0 slightly underpredicts the upper surface pressure peak of the Eppler solution. This reveals a sensitivity of effective fade factor to the leading edge geometry of the airfoil section.

Figures 8 and 9 are used for examination of the effect of angle of attack on the choice of fade factor. Figure 8 displays the CAP–TSD and Eppler solutions for the MS–0313 section at a Mach number of 0.55, an angle of attack of 0°, and a 52–point computational mesh.

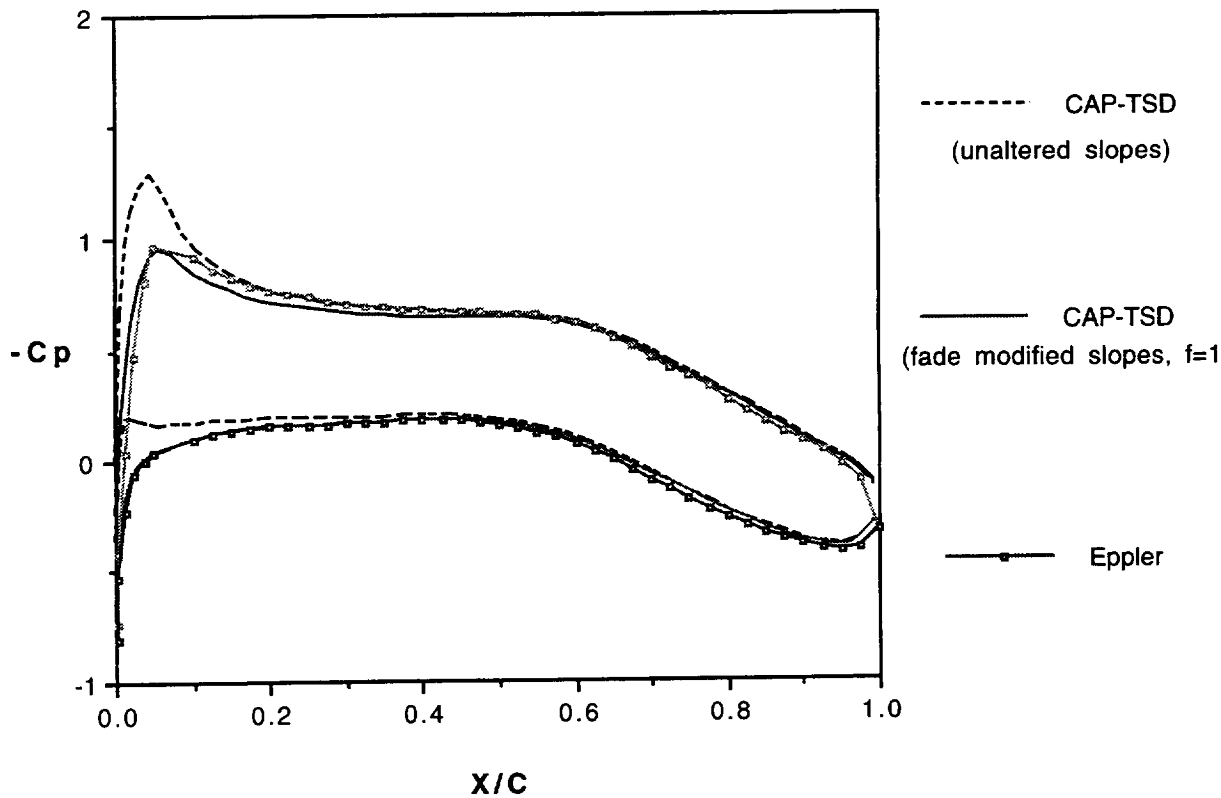

Figure 8: Comparison of CAP–TSD and Eppler Solutions for MS–0313 Airfoil Section, Mach = 0.55, $\alpha = 0^o$

Figure 8 shows that the fading slope modification with a fade factor of 1.0 is in good agreement with the Eppler solution at the upper surface pressure peak. The modified geometry also leads to a significant improvement of the lower surface pressures in the leading edge region. The change in Mach number and angle of attack from the conditions used in the figure 7 comparison appear to improve the effectiveness of this fade factor, f = 1.0.

Figure 9 displays the CAP–TSD and Eppler solutions for the MS–0313 airfoil at a Mach number of 0.55, an angle of attack of 2^o, and a 52–point computational mesh.

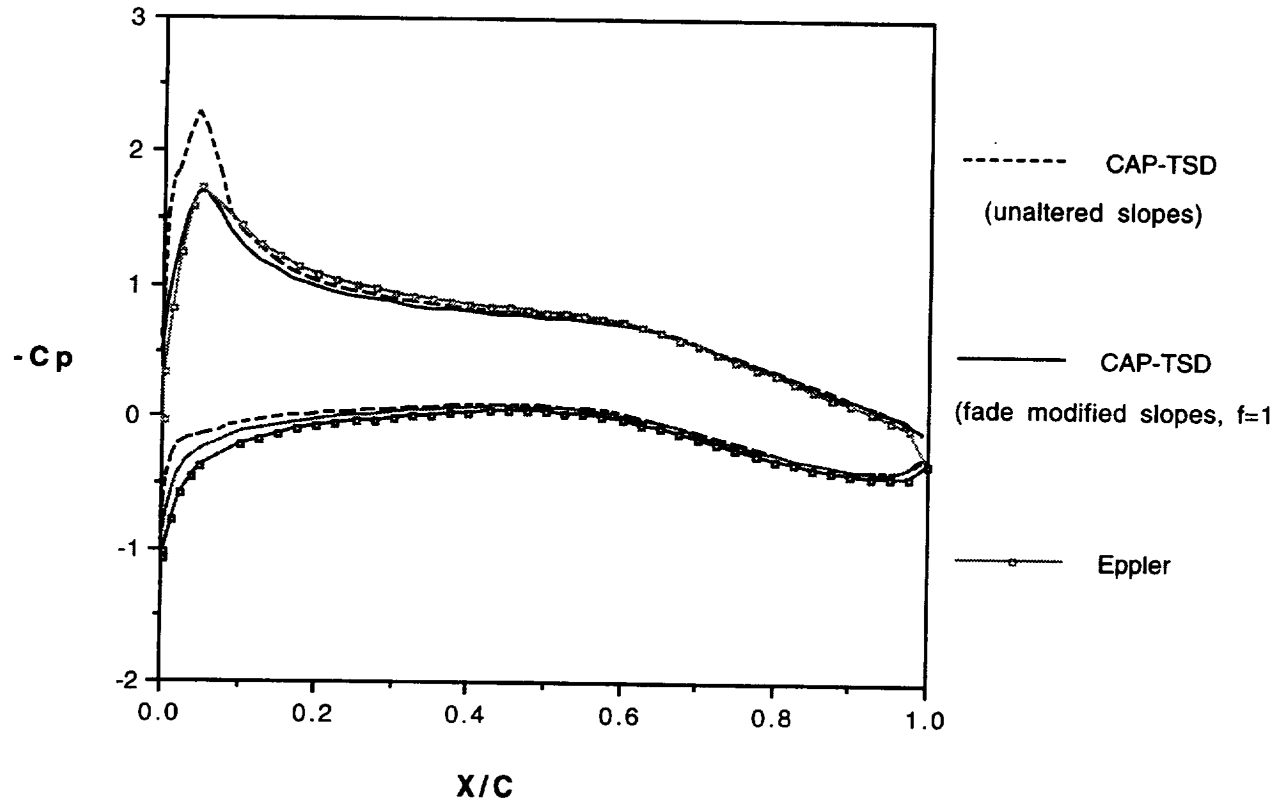

Figure 9: Comparison of CAP–TSD and Eppler Solutions for MS–0313 Airfoil Section, Mach = 0.55, $\alpha = 2^o$

This figure again shows that the fading slope modification with a fade factor of 1.0 is in reasonably good agreement with the Eppler solution. Figures 7, 8, and 9 indicate that the effectiveness of a given fade factor is primarily a function of leading edge bluntness, while angle of attack and Mach number have a less significant influence on the effectiveness of a given fade factor.

Figures 10 and 11 indicate the mesh sensitivity of the CAP–TSD solutions for the fading modified slope and unaltered section geometries. Figure 10 displays the CAP–TSD unaltered section geometry and Eppler solutions for the NLR–7301 section with the computational meshes of 32 and 52 points, a Mach number of 0.6, and an angle of attack of 0^o.

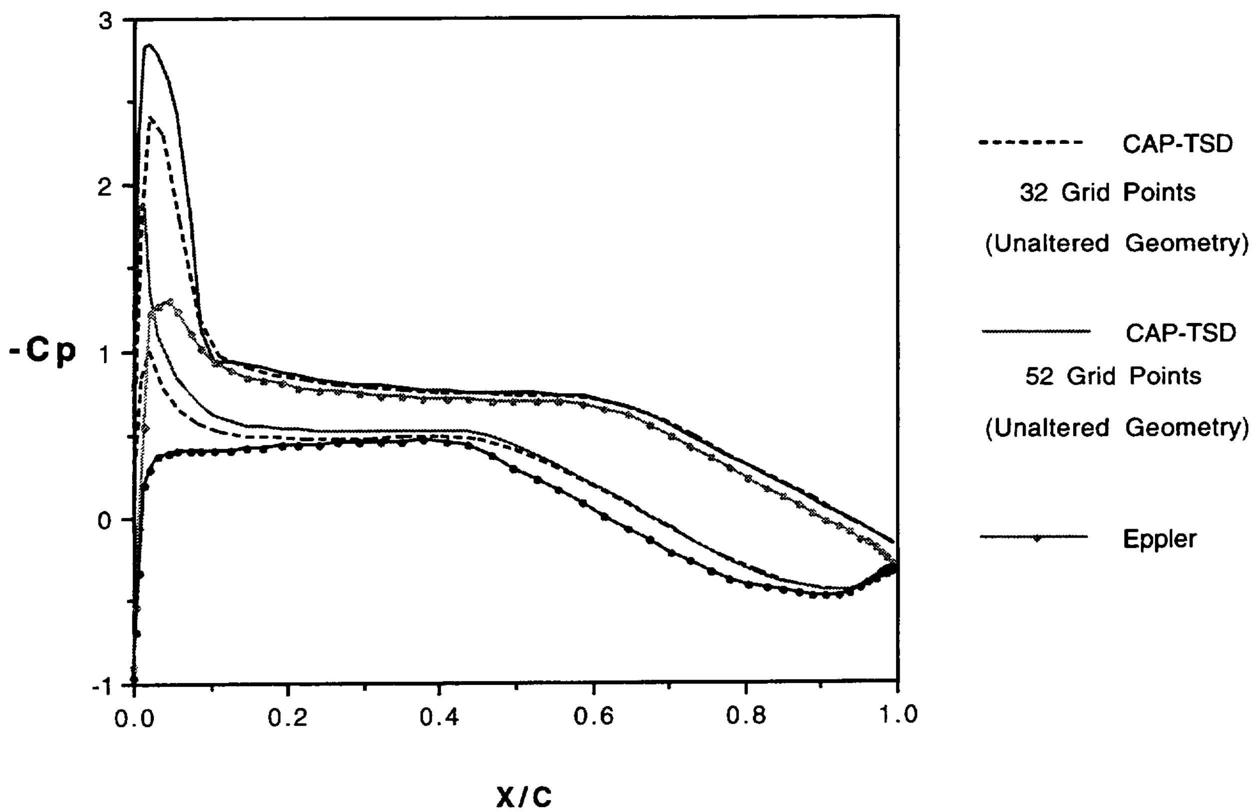

Figure 10: Mesh Sensitivity of CAP–TSD Unaltered Geometry Solutions for NLR–7301 Airfoil Section, Mach = 0.6, $\alpha = 0^o$

Figure 10 reveals the extreme mesh sensitivity of CAP–TSD solutions for the unaltered NLR–7301 geometry. Here the upper surface pressure spikes vary from a coefficient of –2.7 for the 52–point computational mesh to –2.0 for the 32–point mesh.

A secondary goal of the current investigation is to reduce the mesh sensitivity of CAP–TSD solutions. Figure 11 displays the mesh sensitivity of CAP–TSD solutions using the fading slope modified geometry.

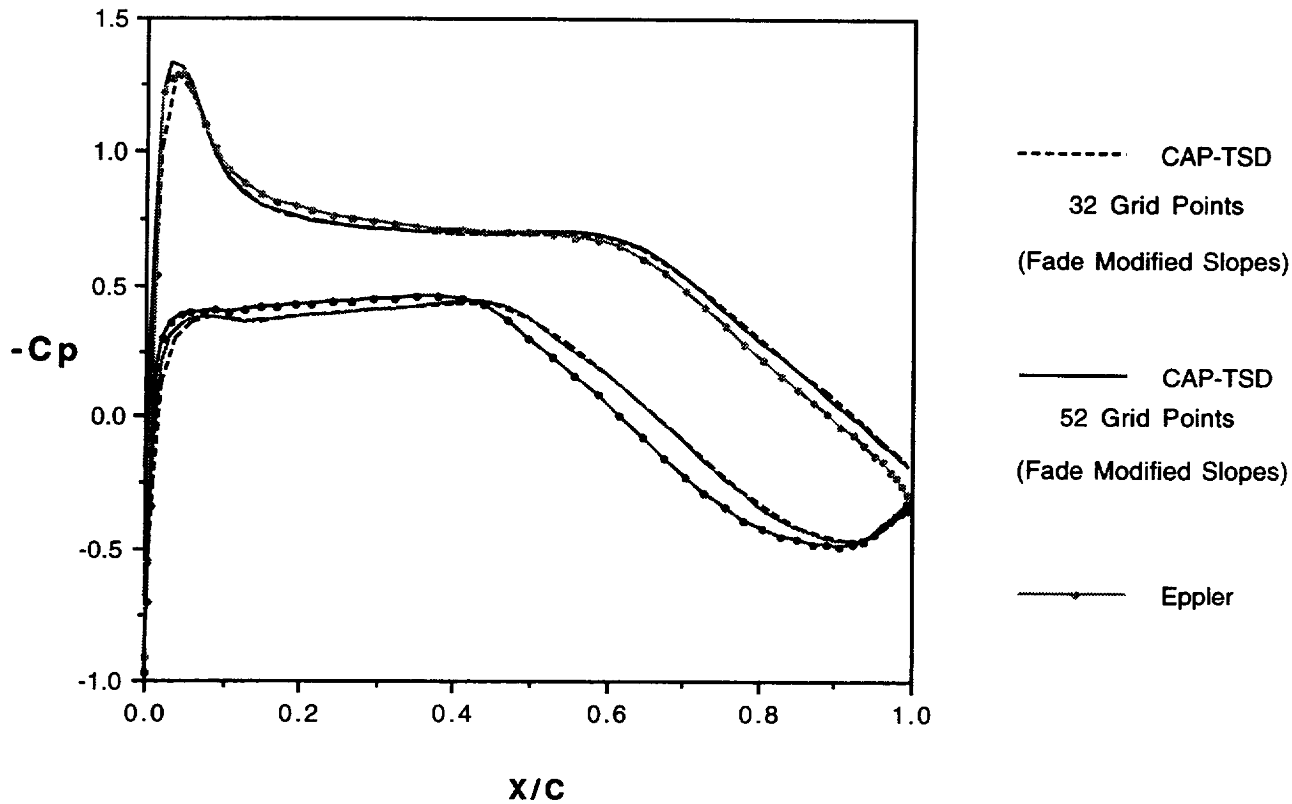

Figure 11: Mesh Sensitivity of CAP–TSD Fading Slope Modified Geometry Solutions for NLR–7301 Airfoil Section, Mach = 0.6, $\alpha = 0^{o}$

Figure 11 shows that the fading slope modification effectively reduces the sensitivity of CAP–TSD solutions to the computational mesh density as well as producing a better comparison with Eppler.

Concluding Remarks and Recommendations

A fading function slope modification of airfoil section geometry is developed and investigated for use in the Computational Aeroelasticity Program—Transonic Small Disturbance (CAP–TSD). The fading modification of slopes is motivated by Riegel's Rule as presented by Van Dyke [6]. The fading modification presented in the current paper alters only the leading

10% of the airfoil section geometry. A fade factor is chosen to match the CAP–TSD solution with an "ideal" solution.

Although the results of the current study are limited in scope, effectiveness of the fading factor appears to be primarily driven by the leading edge bluntness of the airfoil section considered. Effects of possible secondary drivers such as Mach number, angle of attack, and computational mesh density are investigated in limited detail. For the cases examined the effectiveness of the fading factor is not overly sensitive to Mach number, angle of attack, or computational mesh density. However, the effectiveness of the fading factor is highly sensitive to the leading edge geometry of the airfoil section.

For the NLR–7301 [5] section, a fade factor of 1.2 is determined to be appropriate. This fade factor results in a high level of agreement between CAP–TSD and Eppler solutions for the following cases: (1) Mach = 0.6, $\alpha = 0^{\circ}$, mesh = 52 grid points (all meshes considered use a cosine distribution of points); (2) Mach = 0.6, $\alpha = 0^{\circ}$, mesh = 32 grid points; (3) Mach = 0.5, $\alpha = 2^{\circ}$, mesh = 52 grid points.

The second airfoil section used for investigation is that of the MS–0313 [4]. A fade factor of 1.0 is chosen for use of the fading slope modification with the thinner slopes of the MS–0313 section. For the case of Mach = 0.69, $\alpha = -0.75^{\circ}$, and a 52 point mesh, a fade factor of 1.0 slightly underpredicts the upper surface pressure peak. For the two cases of Mach = 0.55 and angles of attack of $\alpha = 0^{\circ}$ and $\alpha = 2^{\circ}$, this fade factor produces pressure predictions in good agreement with Eppler at the upper surface pressure peak.

The fading modification of section slopes as presented in this investigation appears to be a promising means of improving the leading edge pressures predicted by CAP–TSD. A key aspect for the effectiveness of the fading modification is the choice of fade factor. With the proper fade factor, this modification is capable of matching the leading edge pressure peak predicted by CAP–TSD to an "ideal" solution. The results of this investigation suggest that the fade factor is not overly sensitive to angle of attack, Mach number, or computational mesh density. This would mean that the choice fade factor must only be examined once for a given section geometry. Once chosen this factor could be applied arbitrarily to the section without regard to Mach number, angle of attack, or computational mesh density.

Although the results of the current study are encouraging, they are not complete. Due to the limitations of the Eppler code (used for comparison with CAP–TSD solutions), the current investigation examines only subsonic Mach numbers. The effectiveness of the fading slope modification is expected to be unaffected by the change to transonic Mach numbers.

A second and more significant limitation of the current study is the number of airfoil section geometries considered. In order for this modification to be widely and easily applied the correspondence between leading edge geometry and effective fade factor must be determined. This will most likely require extensive investigation of several airfoil sections of varying leading edge bluntness. The NLR–7301 section, used for investigation in this study, is most likely on the high end of leading edge bluntness for airfoil sections of interest. The MS–0313 section, also investigated, is most likely in the mid–range in terms of leading edge bluntness.

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13. ABSTRACT *(Maximum 200 words)*

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