Preliminary Supersonic Analysis Methods Including High Angle of Attack

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The problems associated with predicting the aerodynamic loads for moderate supersonic Mach number, high-angle-of-attack flows and for high supersonic Mach number flows are addressed. For these large-disturbance flows, commonly used prediction methods based on linearized theory or on the tangent-wedge method are shown to be generally inadequate. For the preliminary analysis of aerodynamic shapes subjected to these type flows, two methods have recently been developed by combining features of the linearized theory and the tangent-wedge method. These two new methods are discussed and, through extensive comparisons with experimental data, are shown to offer an improved prediction capability.

Nomenclature

b	= wing span
c	= local wing chord
C_D	= drag coefficient
C_L	= lift coefficient
C_m	= pitching moment coefficient
C_p	= pressure coefficient
ΔC_p	= net load coefficient, lower surface C_p − upper surface C_p
M	= Mach number
x	= distance behind the wing leading edge, measured streamwise
y	= distance from the plane of symmetry
α	= angle of attack
β	$= \sqrt{M^2 - 1}$
δ	= flow deflection angle, the smallest angle between the freestream velocity vector and the plane tangent to the surface
Λ	= wing leading-edge sweep angle

Introduction

SUPERSONIC linear theory has been successfully employed for the analysis of slender configurations at low supersonic Mach numbers for a number of years.[1] Similarly, less slender configurations have been analyzed with varying degrees of success at high supersonic and hypersonic Mach numbers using the tangent wedge and the tangent cone or similar methods. For the analysis of aerodynamic shapes at low supersonic Mach numbers and high angle of attack or for supersonic Mach numbers higher than those of interest for supersonic transports, none of the previously mentioned methods provide consistently accurate results.[2,3] The linear theory assumptions of small disturbances, isentropic shocks, and potential flow become increasingly questionable for high-angle-of-attack flows or at the higher supersonic Mach numbers. The tangent-wedge and tangent-cone methods are not limited by the aforementioned assumptions of linear theory; however, such methods employ no mechanism to account for interference between computational elements.

The violation of the underlying principles of these methods not only explains their inability to predict aerodynamic characteristics at high angle of attack or high supersonic Mach number, but also suggests a possible means of overcoming these problems without resorting to the more complex solutions to the full potential or Euler equations. One obvious approach for lifting surfaces is to combine the supersonic linear theory and the tangent-wedge method in a manner that uses the strength of each method to overcome their respective shortcomings. Specifically, the linear theory calculates the interference between the computational elements, and the interference can be used with the tangent-wedge method, which is more suitable than linear theory for large-disturbance flows. Recently, two methods have been developed which employ this idea of combining the linear theory and the tangent-wedge method. Both of the new methods maintain the relatively small computer resource requirements and versatile geometry input that is characteristic of preliminary analysis methods.

The main purpose of this paper is to provide an assessment of these two new methods by comparing their results with a linear theory method, the tangent-wedge method, and experimental data obtained on simple aerodynamic shapes. First some insight into the problems of the state-of-the-art methods is given, and then the two new methods are described.

Two-Dimensional Supersonic Flow

In order to quantify the error due to linear theory assumptions, it is instructive to consider the simple two-dimensional, attached shock flow over a flat plate inclined at a flow deflection angle δ with respect to the freestream. Figure 1 shows pressure coefficients from the linear and exact inviscid theories for Mach numbers of 2-8 and for flow deflection angles of ± 5 and ± 15 deg; the positive flow deflection angles correspond to a compression, and the negative flow deflection angles correspond to an expansion. The linear theory pressure coefficient is simply $2\delta/\beta$, and the exact inviscid theory pressure coefficient is computed from the oblique shock equations for positive angles and from the Prandtl-Meyer equation for negative angles. There are three things to note from this figure. First, linear theory consistently overestimates the expansion pressure and underestimates the compression pressure. Second, the error in the linear theory pressure increases with both flow deflection angle and Mach number. Third, the linear theory expansion pressure can achieve physically impossible values beyond the vacuum limit, as is illustrated by the intrusion of the linear theory estimate for $\delta = -15$ deg into the cross-hatched region in the figure. Note that the exact theory pressures are bounded by the vacuum limit.

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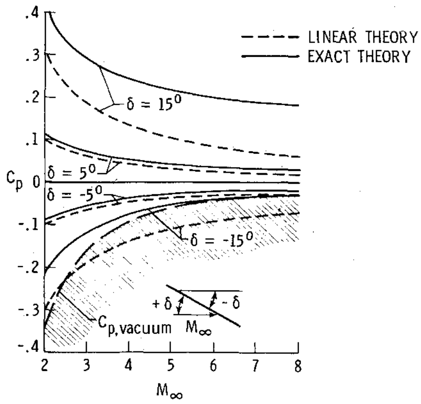

Fig. 1 Linear theory and exact theory pressure coefficients for two-dimensional inviscid supersonic flow.

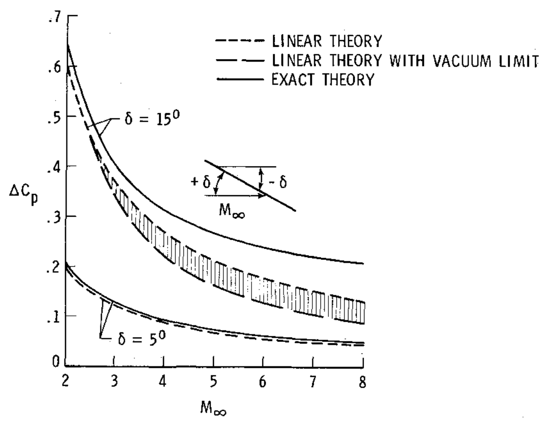

Fig. 2 Linear theory and exact theory net load for two-dimensional inviscid supersonic flow.

A logical means of improving the linear theory pressure results is to impose the vacuum limit. Indeed this improves the linearized theory prediction of expansion pressures; however, it leads to a large degradation in the net load coefficient ΔC_p unless some means is also employed to improve the compression pressure. This is shown in Fig. 2, where the net load coefficient for two flow deflection angles has been constructed by subtracting the expansion pressure coefficient from the corresponding compression pressure coefficient. Because of compensating errors in the compression and expansion linear theory pressures, the net load coefficients of linear theory and exact theory are in much better agreement than one would have expected from the individual pressure coefficients shown in Fig. 1. Also, it is shown in Fig. 2 that any attempt to improve the two-dimensional linear theory results by simply imposing a vacuum limit will cause further error in the net load coefficient.

Three-Dimensional Supersonic Flow

For three-dimensional flows about lifting surfaces at high angles of attack and large Mach numbers, it has become a common practice to impose the vacuum limit on the linear theory prediction of expansion pressures; however, as shown in Fig. 3, this, in general, results in a degradation of the predicted aerodynamic forces just as exhibited by the previously discussed net load coefficient in two-dimensional flows. This figure shows experimental data for an uncambered 76-deg delta wing[4] at $M=4.6$ and the corresponding linear theory estimates[5,6] employing several levels of pressure limitation. A skin friction drag estimate[7] is included in this and all subsequent theoretical drag calculations. The unlimited case predicts the overall C_L and C_D quite well even at high angle of attack, but the unlimited theory shows more

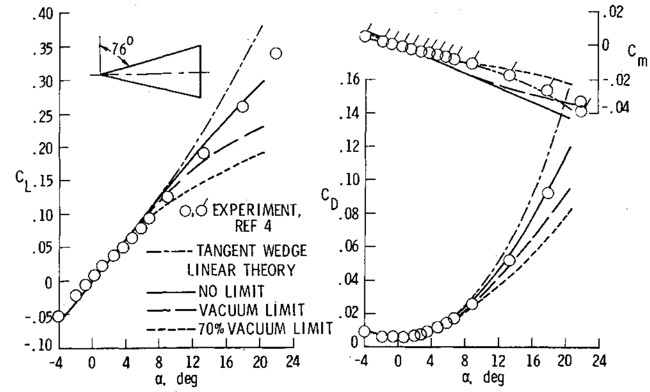

Fig. 3 Effect of pressure limiting on linear theory force and moment estimates for a 76-deg delta wing at $M=4.6$, $\beta\cot\Lambda=1.12$.

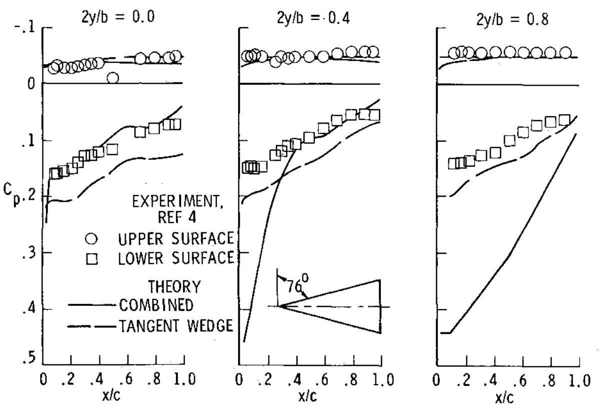

Fig. 4 Experimental data, tangent-wedge method, and combined theory pressure coefficients for a 76-delta wing at $M=4.6$, $\alpha=10.6$ deg.

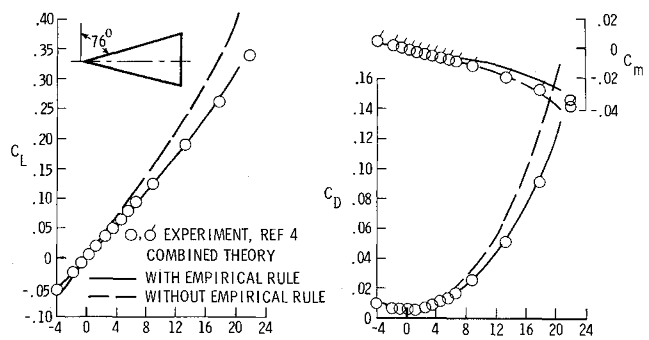

Fig. 5 Effect of the empirical rule on combined theory force and moment estimates for a 76-deg delta wing at $M=4.6$, $\beta\cot\Lambda=1.12$.

longitudinal stability than is obtained experimentally. The accurate force estimates from the unlimited linear theory are fortuitous and obscure the inaccurate predictions of local pressure loads from that method. The application of a vacuum pressure limit degrades the estimates significantly, and limiting the expansion pressure to 70% of vacuum further degrades the results. The 70% vacuum pressure limit on expansion pressures will be applied to all subsequent theoretical calculations. Although this value is somewhat arbitrary, it reflects the fact that a vacuum is never achieved in unconfined fluids.

Figure 3 also presents the tangent-wedge method estimate as calculated from the Douglas Hypersonic Arbitrary Body Program.[8,9] The tangent-wedge method was chosen because it is widely used in hypersonic flow analysis on wedgelike surfaces such as wings. In this procedure, the local flow deflection angle and the freestream Mach number alone determined the local pressure; the oblique shock relations are used to determine compression pressures, and the Prandtl-Meyer equation is used to determine expansion pressures. In the figure, it can be seen that the tangent-wedge method overestimates both C_L and C_D at the higher angles of attack but is accurate at low angles of attack. The pitching moment is accurately predicted for $\alpha < 16$ deg.

Combined Theory

The essence of the combined theory,[10,11] which is based upon the method of aerodynamic influence coefficients (AIC) as developed for the Woodward constant pressure panel code,[5,6] is now summarized. In this method the tangent-wedge method pressure coefficients, as computed in the Douglas Hypersonic Arbitrary Body Program, are modified by the AIC matrix according to the following equation:

$$\Delta C_{p_j} = (\beta/4) a_{ij}^{-1} \Delta C_{p_i}^*$$

where ΔC_{p_j} are the combined theory pressure coefficients, $\Delta C_{p_i}^*$ the tangent-wedge pressure coefficients, and a_{ij}^{-1} the linear theory influences of all panels i on panel j.

As shown in Fig. 4, combined theory pressures exhibit the classical linear theory trend of extremely large pressure estimates near the leading edge. This problem was corrected by employing the following empirical rule suggested in Ref. 10: compare combined theory pressures with tangent-wedge pressures, and use the lesser of the two for the subsequent force and moment summation. The empirical rule will, therefore, result in the truncation of the excessively large leading-edge compression pressures calculated in the combined theory method. The effect of this correction on the force and moment data for the 76-deg delta wing is shown in Fig. 5. The C_L and C_D estimates are markedly improved, but the C_m estimate actually deteriorates. Further comparisons by the present author indicated that the empirical correction should not be used in all cases, but should be limited to values of $\beta\cot\Lambda < 2.3$.

The combined theory as originally presented made use of a "scale factor" to approximately adjust the AIC matrix to account for the variation in the size of the Mach cone with angle of attack. For a given M_∞ and positive angle of attack, the Mach number behind the shock, M_2, can be determined from the oblique shock relations. Since the Mach number behind the shock is lower than M_∞, the region of influence will be greater by a factor of $\tan[\cos^{-1}(1/M_\infty)]/\tan[\cos^{-1}(1/M_2)]$. On the expansion surface, the region of influence will be decreased. Figure 6 shows the effect of the scale factor on the force and moment estimates. In both cases, the empirical rule discussed in the previous paragraph was utilized. The scale factor is seen to degrade the combined theory estimate for C_L and C_D while offering some improvement in C_m. The concept of this scale factor is physically reasonable, but the results do not justify its use.

Modified Linear Theory

The modified linear theory[12-15] utilizes an "effective" flow deflection angle that consists of the geometric flow deflection angle plus an induced angle calculated by a linear theory chord plane method. This induced angle represents the influence of lifting elements within the fore Mach cone expressed as a Prandtl-Meyer angle. In this method, the "effective" flow deflection angle and the freestream Mach number determine the pressure using the oblique shock equations for positive angles and using the Prandtl-Meyer equation for negative angles. This is procedurally the same as the tangent-wedge method, the difference being the use of the "effective" flow deflection angle as opposed to the geometric flow deflection angle. So, both the combined theory and the modified linear theory use linear theory influence factors in conjunction with the oblique shock and Prandtl-Meyer

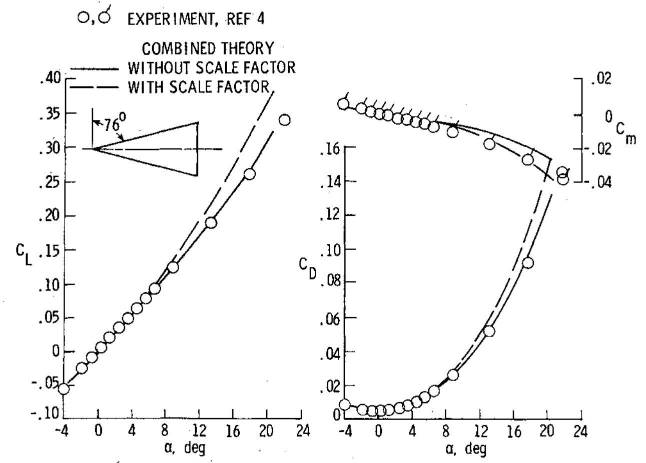

Fig. 6 Effect of the scale factor on combined theory force and moment estimates for a 76-deg delta wing at $M = 4.6$, $\beta\cot\Lambda = 1.12$.

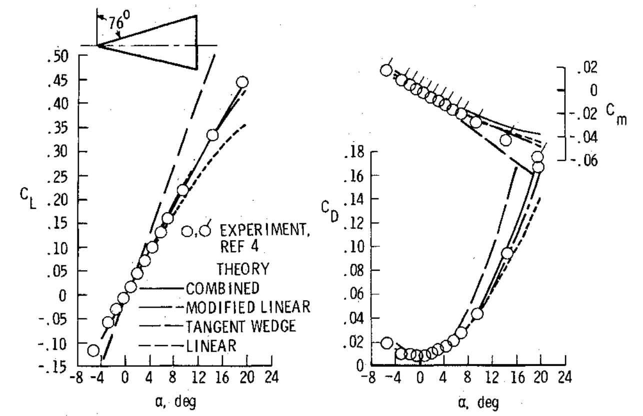

Fig. 7 Calculated and experimental force and moment data for a 76-deg delta wing at $M = 2.3$, $\beta\cot\Lambda = 0.52$.

equations, but at different points in the procedure; i.e., the combined theory corrects the nonlinear C_p after they are calculated, whereas, the modified linear theory corrects the flow deflection angle used to determine the nonlinear C_p.

The modified linear theory also addressed the nonlinear flow about the wing leading edge by including an estimate of attainable leading-edge thrust for a subsonic leading-edge wing in supersonic flow. The portion of the full theoretical leading-edge thrust that is not attained is presumed to act normal to the chord plane and is treated as a vortex increment. The concept of a rotated suction force vector was originally developed by Polhamus.[16]

Comparison of Theory and Experimental Data

Thin Wings

The linear theory, tangent-wedge method, combined theory, and the modified linear theory are now compared with experimental data for a wide range of supersonic and hypersonic Mach numbers.

Figure 7 presents the force and moment data for the 76-deg delta wing[4] at $M = 2.3$ ($\beta\cot\Lambda = 0.52$). The new methods, i.e., combined theory and modified linear theory, both predict C_L and C_D quite well across the entire angle-of-attack range, whereas the tangent-wedge method overpredicts these forces even at $\alpha = 0$ deg, and the linear theory is accurate for $\alpha \leq 8$ deg but underpredicts the forces at the moderate to high angles of attack. The modified linear theory estimate of C_m agrees very well with the data for $\alpha \leq 8$ deg, but above that point predicts too much nose-up C_m. The combined theory provides a poorer estimate and shows reduced static stability across the entire angle-of-attack range.

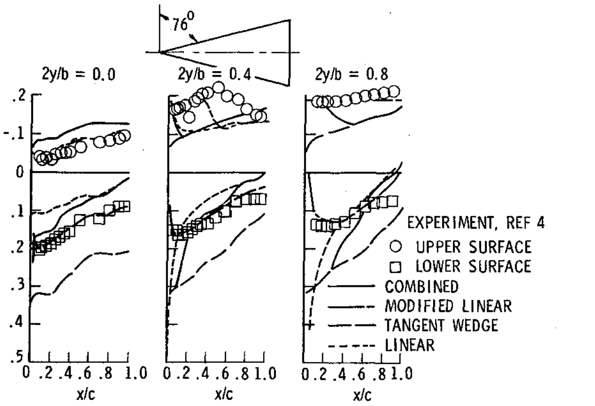

Fig. 8 Calculated and experimental pressure data for a 76-deg delta wing at $M=2.3$, $\alpha=9.9$ deg.

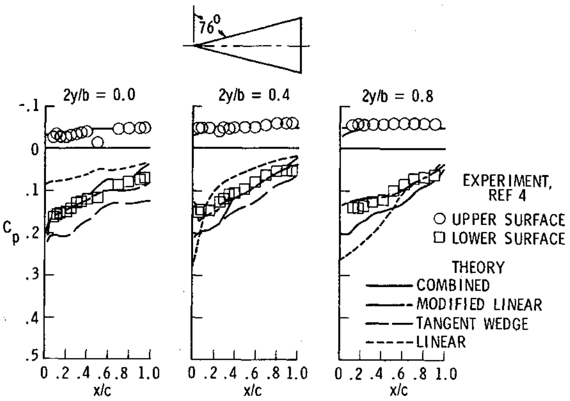

Fig. 10 Calculated and experimental pressure data for a 76-deg delta wing at $M=4.6$, $\alpha=10.6$ deg.

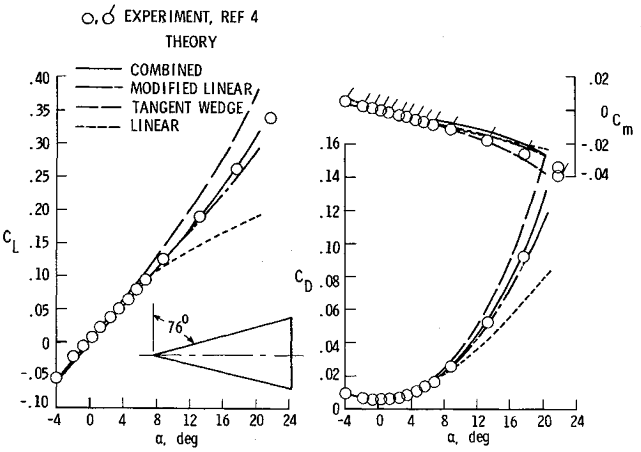

Fig. 9 Calculated and experimental force and moment data for a 76-deg delta wing at $M=4.6$, $\beta\cot\Lambda=1.12$.

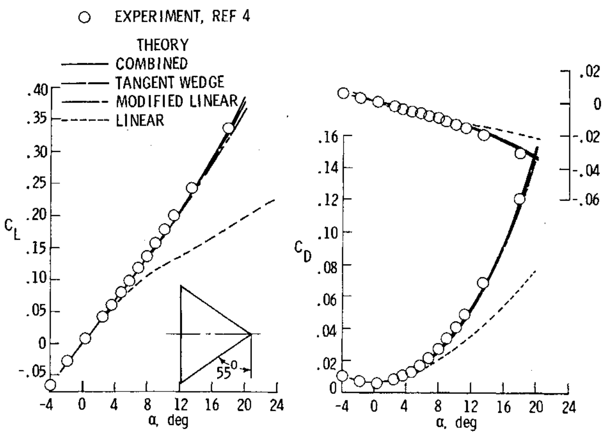

Fig. 11 Calculated and experimental force and moment data for a 55-deg delta wing at $M=4.6$, $\beta\cot\Lambda=3.14$.

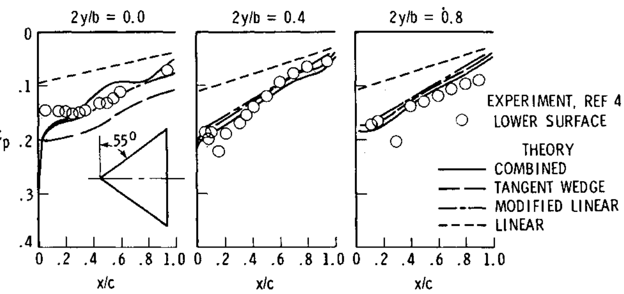

Fig. 12 Calculated and experimental pressure data for a 55-deg delta wing at $M=4.6$, $\alpha=9.2$ deg.

More insight into the differences between the various methods can be observed from the surface pressure data in Fig. 8. In this figure, the longitudinal distribution of pressure coefficient is presented at three different span stations at $\alpha=9.9$ deg and $M=2.3$ for the 76-deg delta wing. The compression pressure coefficients clearly reflect the trends that were observed in the C_L and C_D estimates, namely, that the linear theory underpredicts, the tangent-wedge overpredicts, and the two new methods fall generally in between. The modified linear theory clearly provides the most accurate estimates of pressure coefficient for both the upper and lower surfaces, although the compression pressure coefficient at the leading edge tends toward zero in the wing-tip region. However, the combined theory estimate has the opposite problem: that of an extremely large overprediction of the pressure coefficient at the leading edge, which upon integration yields reduced static stability, as was noted in Fig. 7. The effect of the previously discussed empirical rule is quite apparent in Fig. 8, where the merging of the combined theory pressure coefficient with the tangent-wedge pressure coefficient is seen. Also, note in Fig. 8 for span station $2y/b=0.4$ the presence of a distinct "bump" in the modified linear theory pressure coefficients on the upper surface. This is the vortex increment calculated by that method. Additionally, the experimental data clearly show that the flow can expand beyond 70% of vacuum ($C_p=-0.189$) at $M=2.3$.

Force and moment data and pressure data for the 76-deg delta at $M=4.6$ ($\beta\cot\Lambda=1.12$) are shown in Figs. 9 and 10, respectively. Even though the Mach number doubled relative to the previous case, the trends of the various methods relative to the experimental data are virtually unchanged. By observing the relationship of the various theoretical estimates with the experimental data for increasing Mach number, it is seen that the tangent-wedge estimates improve, but are still significantly in error except at low angle of attack. Likewise, for the linear theory, a distinct deterioration in the predictions is noted for increasing Mach number, although the low-angle-of-attack estimates of C_L and C_D are still accurate. As a reminder, Fig. 2 showed that the linear theory ΔC_p was very close to that from exact, inviscid theory for small flow deflection angles up through Mach 8 for the two-dimensional case. Both of the new methods are superior to the other two methods across the supersonic Mach number range, especially for the difficult high-angle-of-attack problem.

Figure 11 presents force and moment data for a 55-deg delta wing[4] at $M=4.6$ ($\beta\cot\Lambda=3.14$). For this supersonic leading-edge case, the tangent-wedge method, combined theory, and modified linear theory provide very similar estimates that agree well with the experimental data; however, the linear theory estimates are seen to be inadequate. The

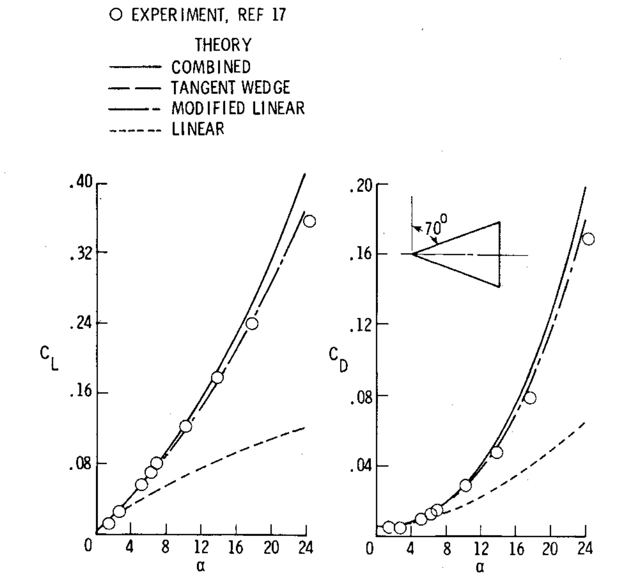

Fig. 13 Calculated and experimental force data for a 70-deg delta wing at $M=6.9$, $\beta\cot\Lambda=2.48$.

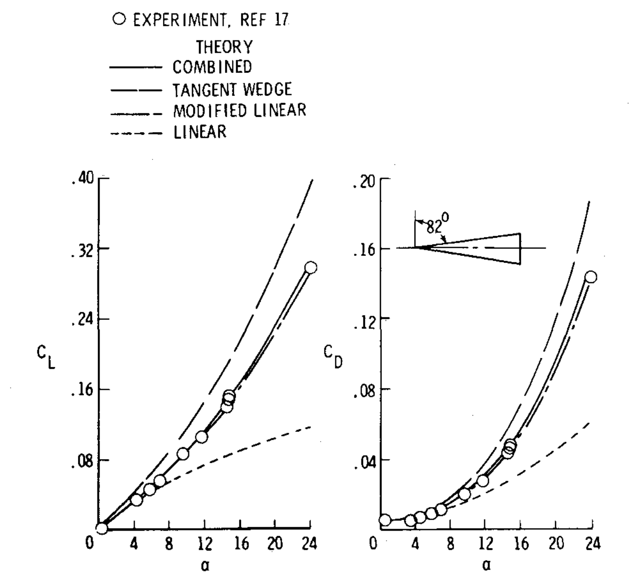

Fig. 14 Calculated and experimental force data for an 82-deg delta wing at $M=6.9$, $\beta\cot\Lambda=0.96$.

no longer limits the compression pressure coefficient in the combined theory calculations because $\beta\cot\Lambda>2.3$.

As an example of a hypersonic Mach number case, force results are shown on a 70-deg delta wing and an 82-deg delta wing at $M=6.9$ in Figs. 13 and 14, respectively. Both wings compression pressure coefficients for this case at $\alpha=9.2$ deg are shown in Fig. 12. The accuracy of the force and moment estimates are borne out by this figure, where both the pressure coefficient levels and trends are generally well predicted by all methods except the linear theory. Note that the empirical rule have 5% thick diamond airfoil sections. In Fig. 13, the combined theory and the tangent-wedge method estimates for the 70-deg delta wing ($\beta\cot\Lambda=2.48$) are essentially identical because of the narrow Mach cone and the relatively small level of interference between computational panels with supersonic leading edges. The modified linear theory estimates are slightly below those of the combined theory and tangent-wedge method, which is the same trend that was apparent for the supersonic Mach number cases. The linear theory estimates are totally inadequate above $\alpha=3$-4 deg. Note that the combined theory/tangent-wedge method estimate is quite accurate for $\alpha\leq 14$ deg, but above that point the slope of the experimental data changes markedly. This is because the basic flow characteristics change past the angle of leading-edge shock detachment, which is about 8 deg for this case.[17] Figure 14 for the 82-deg delta wing is a subsonic leading-edge case ($\beta\cot\Lambda=0.96$), so that there is no region of two-dimensional flow, and, therefore, the combined theory and tangent-wedge method estimates are quite different. The combined theory and the modified linear theory agree well with each other and the experimental data across the entire angle-of-attack range. The comments on linear theory apply as before.

Thick Elliptic Cone

In order to explore the limits of the methods further, a 70-deg swept delta wing with a 3:1 elliptic cross section was investigated at $M=4.5$ ($\beta\cot\Lambda=1.60$).[18] The wing is 24% thick at the centerline and over 100% thick in the tip region. The experimental force and moment results shown in Fig. 15 are unpublished NASA data; the pressure coefficient data shown in Fig. 16 are presented in Ref. 18. The trends of the force and moment estimates from the four calculation methods with respect to the experimental data are similar to those seen in the data/theory comparison for thin wings. Overall, the new methods do not estimate the forces and moments as well as for thin wings, but the most surprising result is the extremely large overprediction of C_D from the modified linear theory method. Investigation of this problem

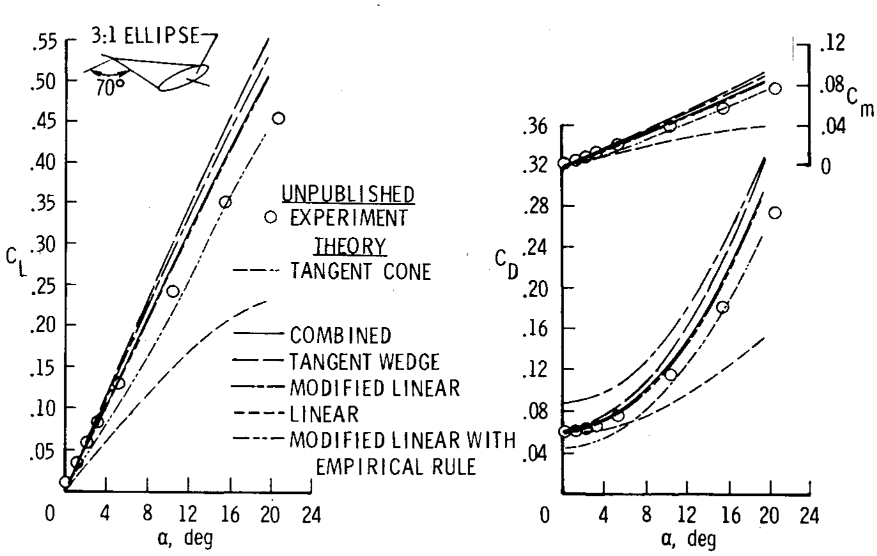

Fig. 15 Calculated and experimental force and moment data for a 3:1 elliptic cone, 70-deg sweep, $M=4.5$, $\beta\cot\Lambda=1.60$.

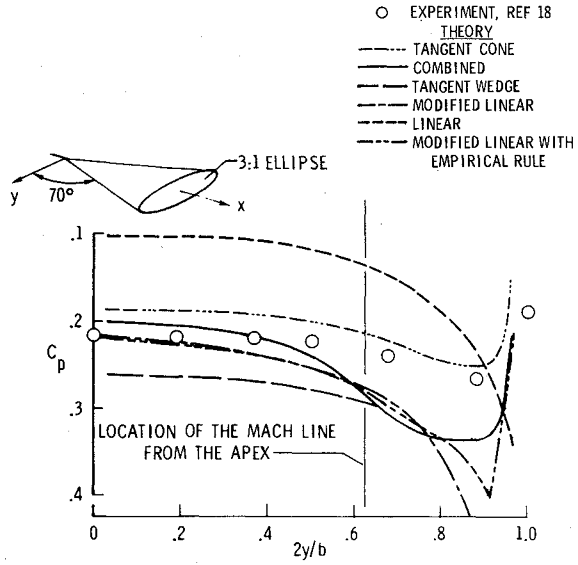

Fig. 16 Calculated and experimental pressure data for a 3:1 elliptic cone, 70-deg sweep, $M = 4.5$, $\alpha = 9.5$ deg.

revealed that the modified linear theory significantly overestimated the leading-edge compression pressure coefficients, especially in the tip region where the maximum thickness ratios for the model were in excess of 1.0. This problem was not encountered for the modified linear theory estimates for thin wings with supersonic leading edges (Figs. 10 and 12). Several attempts were made at reformulating the critical parameter for the thickness solution in a way that would more accurately reflect the physics of the flow, but none of these alterations proved satisfactory. The approach that provided the best overall result for the modified linear theory was simply to employ the empirical rule used for all wings in the combined theory calculations.

A method that is more appropriate than the tangent wedge for the elliptic-cone case is the tangent-cone method. This procedure is similar to the tangent-wedge method except that the local compression pressures are determined from the cone tables instead of the oblique shock equations. Figure 15 shows that the tangent-cone estimates of C_L and C_m are generally more accurate than those of the other methods, but the C_D is significantly underestimated.

Surface pressure data for $M = 4.5$ and $\alpha = 9.5$ deg at the trailing edge of the wing are presented in the lateral direction in Fig. 16. The calculations shown are the four previously discussed methods, the modified linear theory with the empirical rule, and the tangent-cone method. The large pressure coefficient estimates from modified linear theory in the tip region are immediately evident, as is the large error in the linear theory pressure coefficient. The location at the trailing edge of the Mach cone emanating from the apex is indicated in the figure as a vertical line. Note that the empirical rule, which limits both combined theory and modified linear theory pressure coefficients to values no greater than tangent-wedge pressure coefficients, dominates the combined theory and modified linear theory outboard of the Mach line. The tangent-cone pressure estimates show an accurate trend across the entire semispan, although they somewhat underestimate the pressure level. None of these simplified methods applied to this problem were completely satisfactory, but the new methods provided better results than the tangent-wedge method and the linear theory.

Conclusions

Supersonic linear theory and a hypersonic method suitable for preliminary analysis in the supersonic Mach number range were shown to be inadequate for the estimation of aerodynamic loads for high-angle-of-attack flow conditions or for high supersonic Mach number conditions. Two independent researchers have combined the supersonic linear theory and the tangent-wedge method into two new methods in an effort to provide improved aerodynamic predictive capability for these conditions. This was done in a manner which retained the strengths of each of the preliminary analysis methods, viz., aerodynamic interference from supersonic linear theory, more accurate noninterference pressure estimates from the tangent-wedge method, and low computer resource requirements and versatile geometry input method, showed that each new method provided improved estimates of forces, moments, and pressures for thin wings from both methods. The evaluation of the two new methods (combined theory and modified linear theory), along with a supersonic linear theory method and the tangent-wedge across an extremely wide range of Mach numbers and angles of attack, and that the modified linear theory was superior to the combined theory. These conclusions are equally valid for the very difficult case of the thick elliptic cone at $M = 4.5$, although the quality of the estimates was not as good as for the thin-wing case.

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EXPERIMENTAL DIAGNOSTICS IN COMBUSTION OF SOLIDS—v. 63

Edited by Thomas L. Boggs, Naval Weapons Center, and Ben T. Zinn, Georgia Institute of Technology

The present volume was prepared as a sequel to Volume 53, *Experimental Diagnostics in Gas Phase Combustion Systems,* published in 1977. Its objective is similar to that of the gas phase combustion volume, namely, to assemble in one place a set of advanced expository treatments of the newest diagnostic methods that have emerged in recent years in experemental combustion research in heterogenous systems and to analyze both the potentials and the shortcomings in ways that would suggest directions for future development. The emphasis in the first volume was on homogenous gas phase systems, usually the subject of idealized laboratory researches; the emphasis in the present volume is on heterogenous two- or more-phase systems typical of those encountered in practical combustors.

As remarked in the 1977 volume, the particular diagnostic methods selected for presentation were largely undeveloped a decade ago. However, these more powerful methods now make possible a deeper and much more detailed understanding of the complex processes in combustion than we had thought feasible at that time.

Like the previous one, this volume was planned as a means to disseminate the techniques hitherto known only to specialists to the much broader community of reesearch scientists and development engineers in the combustion field. We believe that the articles and the selected references to the current literature contained in the articles will prove useful and stimulating.

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