DEVELOPMENT OF AN AERODYNAMIC THEORY CAPABLE OF PREDICTING SURFACE LOADS ON SLENDER WINGS WITH VORTEX FLOW

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SUMMARY

With advent of supersonic cruise aircraft that utilize vortex lift at some point in their flight envelope, the need for an analytical method capable of accurately predicting loads on wings with leading-edge separation has become evident. The Boeing Commercial Airplane Company, under contract to NASA Langley Research Center, has developed an inviscid three-dimensional lifting surface method that shows promise in being able to accurately predict loads, subsonic and supersonic, on wings with leading-edge separation and reattachment.

INTRODUCTION

For the thin, relatively sharp edge, highly swept-back wings of interest for supersonic cruise aircraft, the leading-edge vortex type of flow and resulting vortex lift characteristics are important design considerations. In addition to its well known high lift capability, this flow phenomena provides a highly stable and consistent flow pattern over a wide range of flight conditions, and for several modern supersonic aircraft, this type of flow is basic to the aerodynamic design concept. In addition, the critical wing structural loads for a wide variety of high speed aircraft are generated in angle-of-attack ranges where this type of flow tends to predominate. As part of its research program directed towards developing theoretical methods for the design and analysis of wings for advanced high speed aircraft, the Langley Research Center has contracted with the Boeing Commercial Airplane Company for the development of a method for the prediction of aerodynamic load distributions of wings with nonconical leading-edge vortex flow. This paper is presented as a progress report on this work, bringing forward the motivation for this research program, the objectives of the work, and some selected results.

SYMBOLS

b	model span
c	local chord
C_L	lift coefficient, $\frac{\text{lift}}{qS}$
C_p	pressure coefficient, $\frac{p-p_{ref}}{q}$
ΔC_p	lower surface C_p minus upper surface C_p
M	free-stream Mach number
n	unit normal vector
p	local static pressure
p_{ref}	reference pressure
q	free-stream dynamic pressure
S	reference area
U_∞	free-stream velocity
V	local velocity vector
x	chordwise coordinate
y	spanwise coordinate
α	angle of attack, deg
ρ	density of air
ε_{tip}	Twist angle of wing tip, positive leading edge up

SOME APPLICATIONS OF VORTEX FLOW

Figure 1 shows a slender wing at angle of attack with associated leading-edge vortex. Shown on the right hand side of the figure is a plot of lift coefficient versus angle of attack illustrating the large amount of vortex lift developed. Presently, analytical techniques are available for computing the total lift versus angle of attack for wings having leading-edge vortices at subsonic and supersonic speeds (references 1 and 2). There are, however, no methods available that accurately predict the load distribution on wings with leading-edge vortices nor are there any design methods that will allow the optimization of vortex flow. The prediction of loads on wings due to leading-edge vortex separation is an important problem to the structural designer and aeroelastician, since supersonic cruise vehicles either depend on or encounter vortex lift at many points in their flight envelope. Figure 2 presents some examples of aircraft that utilize vortex lift in their design.

Supersonic Cruise Transports

The wing geometry, thin and highly swept, for this type of aircraft is conducive to forming leading-edge vortices. For current supersonic cruise transports vortex lift is used as a simple, lightweight, high-lift system employed at take-off and landing, and because of the highly stable nature of the flow, it is utilized throughout a large part of the flight envelope. Even if the design concept called for suppression of the vortex at several points in the envelope by means of variable geometry devices, many conditions would be expected to exist where vortex flow still predominates. This is due to the differences in attached flow geometry requirements through the speed range and the large variations in lift relative to the design point. The large lift variations are illustrated in figure 3 for a typical slender wing transport where both the level flight and the 2.5 g structural load requirement is shown. It is apparent that both the structural loads and the design of any flow control devices will require the prediction of vortex flow characteristics even if this flow is not basic to the design concept.

Strategic Reconnaissance Aircraft

For this particular supersonic cruise aircraft, vortex lift is used to produce low-speed high lift, aerodynamic center control throughout the Mach number range and for improved directional stability characteristics.

Supersonic Cruise Fighters

Many of the implications regarding vortex flow discussed relative to the supersonic cruise transport would be expected to hold true for supersonic cruise fighters. In addition, vortex lift generated by the slender wing would, in all probability, be utilized for transonic maneuvering just as vortex lift strakes are basic to the design of current lightweight fighters.

It becomes apparent that a knowledge of the load distribution associated with the leading-edge vortex is needed early enough in the design of these supersonic cruise aircraft so that the aircraft will not be penalized with a structural weight penalty and that the most efficient trades between the aerodynamic and structural design can be made.

ANALYTICAL TOOLS CURRENTLY AVAILABLE

Although attached flow theory would not be expected to predict load distribution on wings with leading-edge vortex flow, current computer aided design and analysis methods are limited to attached flow theories. The data in figures 4(a) and (b) are presented to show the magnitude of the errors involved in using these methods. (These data in figure 4 are obtained from references 3 and 4.) The data in figures 4(a) and (b) are for Mach numbers 0.85 and 1.70; the theories shown are the Boeing TEA-230 program and FLEXSTAB. As was expected, the agreement between theory and experiment is poor and points up the magnitude of the problem. Since aeroelastic prediction techniques are also based on attached flow theories, the aeroelastic predictions on wings having leading-edge vortex flow also is poor. The data in figure 5 shows a comparison of aeroelastic prediction and experimental data for a highly swept wing at a Mach number of 0.85 (ref. 3). The triangular symbols are experimental data for a flat wing and the circular symbols are experimental data for a wing with the same geometric characteristics except it has a twist distribution. Using attached flow theory, the flat wing experimental data are corrected to represent data for a wing with the same twist distribution as that of the second wing. As can be seen, the agreement between experiment and theory is quite poor. It should be noted here that the agreement between experiment and theory for supersonic Mach numbers is also poor (ref. 4).

Until fairly recently, attempts to account for the vortex flow effects on wing load distributions have been based on conical flow assumptions in order to make the difficult mathematical modeling problem more tractable. While important contributions have been made by these conical flow studies, the improvements over attached flow theories are insufficient to satisfy the needs of the designer. As a short review, figure 6 shows a comparison of experiment and Smith's conical flow method (ref. 5). At the particular x/c station chosen, the agreement between experiment and Smith's theory is poor and, in fact, since the conical flow method does not satisfy the Kutta condition at the trailing-edge, it should be expected that the agreement between experiment and theory would worsen as the trailing-edge is approached. Linear attached flow lifting surface theory results are presented on figure 6 simply as a reference.

OBJECTIVES OF RESEARCH PROGRAM

The NASA Langley Research Center, realizing the potential benefits of having an analytical method of computing load distributions on wings with vortex flows, embarked on a research program with the objectives discussed below. The Boeing Commercial Airplane Company was awarded a contract to develop a 3-D lifting surface theory for analysis of aerodynamic characteristics and structural loads for configurations having free vortex flows at subsonic and supersonic speeds with arbitrary wing geometry. Having developed the theory, it would be evaluated by numerical and wind tunnel experimental studies. The final goal of this research program is to develop design modules needed for computer aided design methods for application to supersonic and hypersonic cruise vehicles.

PANEL SCHEME

Figure 7 shows a typical panel arrangement for the wing and its vortex sheets. The wing is paneled with quadraticly varying strength doublet panels and linearly varying source panels. The boundary conditions on the wing are no flow through the wing and the Kutta condition at all edges is satisfied if the wing is thin; however, if the wing has thickness, the vortex sheet separation point can be moved aft of the leading edge to study the effect of moving the separation point.

All the vortex sheets are paneled with quadraticly varying doublet panels. The boundary conditions on the free-vortex sheet are no flow through the vortex sheet and that the vortex sheet be locally force free.

The fed sheet is a simplified model of the physical vortex core region. For the results presented in this paper, the fed sheet is a kinematic extension of the free sheet. The assumption in this model is that the boundary conditions applied to the free sheet are adequate to position the fed sheet. Current work is on going to improve the fed sheet model.

The trailing wake shape is frozen from the trailing edge to infinity. However, with the trailing-edge swept (arrow wing or cropped arrow wing), it has been found that the wing loadings in the vicinity of the trailing edge are highly sensitive to the trailing-edge sweep. As a temporary fix to this problem, the near wake region has an additional boundary condition, $\Delta C_p = 0$. This seemed to improve the loadings on the wing, but caused serious problems with convergence. It is presently planned for future work to allow the wake to roll up rather than freezing the wake shape at the trailing edge. For further details, the reader is referred to references 6 and 7.

RESULTS AND DISCUSSION

Figure 8 presents results from the Boeing nonconical theory for an aspect ratio 2 delta wing. Since it has been shown in reference 1 that the suction analogy agrees well with experimental data, the suction analogy is used here as a bench mark. The attached flow theory and Smith conical flow theory (ref. 5) are presented as references. The symbols are results for the Boeing nonconical flow theory; it can be seen that the present theory agrees well with the suction analogy. On the plot of ΔC_p versus semispan station, it is observed that the present theory appears to be correctly handling the Kutta condition at the trailing edge, since the pressure levels decreased as the trailing edge is approached.

The comparison of theroetical and experimental (ref. 8) load distributions are presented in figure 9. These results are for an aspect ratio 1.46 delta wing at 14 degrees angle of attack at incompressible speeds. It is seen that the present theory agrees very well with experiment. Again, attached flow and conical flow theories are shown as references.

Figure 10 shows results for a thick wing with a swept trailing edge. This is a plot of ΔC_p versus x and the wing is at an angle of attack of 11.9^o. The leading-edge vortex sheet is assumed to be shed from the wing leading edge. Because of the near wake problem discussed earlier, the solution for this problem is not converged; however, the results do look very promising.

CONCLUDING REMARKS

Langley Research Center and the Boeing Commercial Airplane Company are engaged in a joint research program to develop and evaluate an analytical method capable of computing load distributions on swept wings with leading-edge vortices. Boeing, having developed the method, is working to improve the fed sheet model, to improve the computational efficiency, to increase the number of panels that may be used, and to add compressibility and general configuration capability (fuselage and thickness). In the near future, the Boeing Commercial Airplane Company will start developing a supersonic theory for the method, add wake roll up, and carry out an extensive evaluation of the existing method.

Langley Research Center will evaluate the method by numerical and wind-tunnel experiments. The design capability will be exercised to optimize vortex lift characteristics for supersonic cruise and maneuvering aircraft by combining vortex flow with thickness, camber, and twist distributions. Finally, the design capability will be evaluated by wind-tunnel tests.

The preliminary results are very promising and it appears that the approach will eventually provide the capability needed for optimizing and controlling vortex lift and for predicting the wing aerodynamic loads at the critical structural design conditions for slender wing aircraft.

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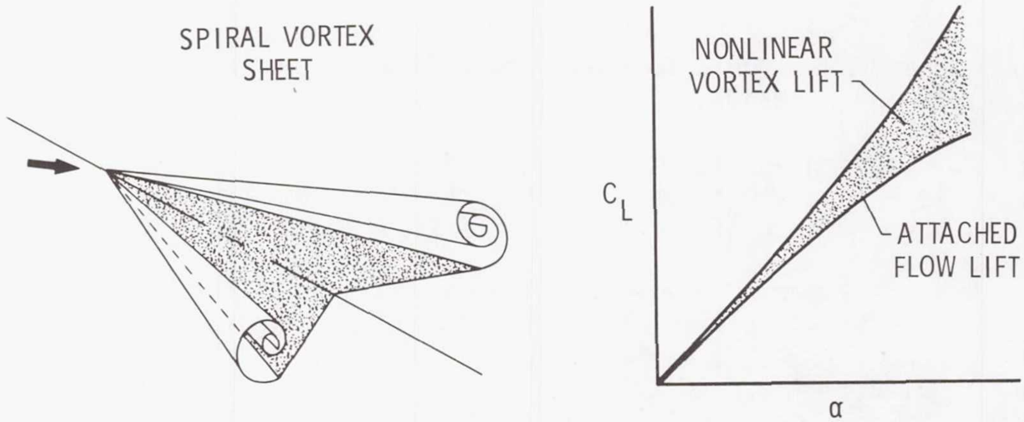


Figure 1.- Leading-edge vortex flow.

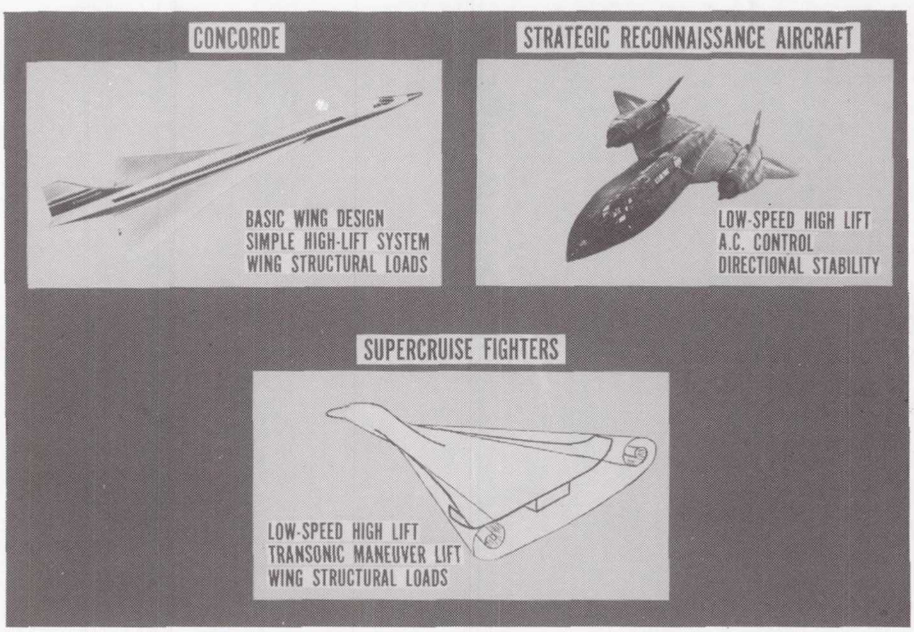


Figure 2.- Examples of aircraft that utilize vortex lift.

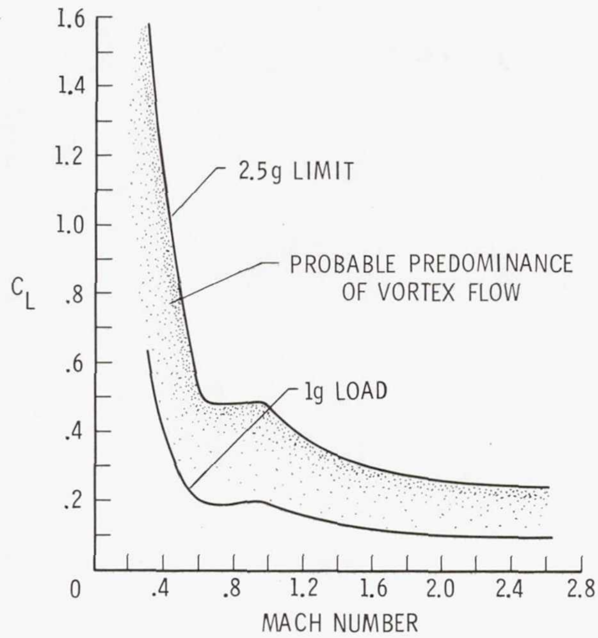
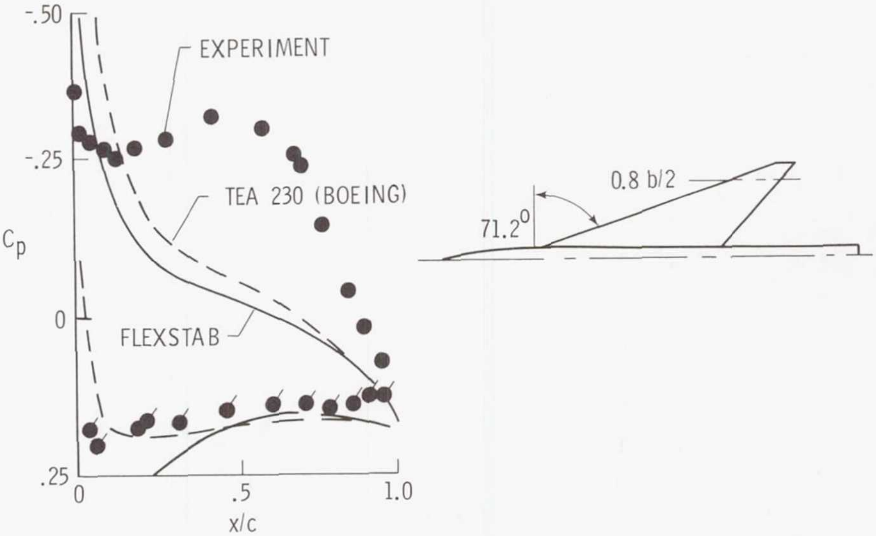
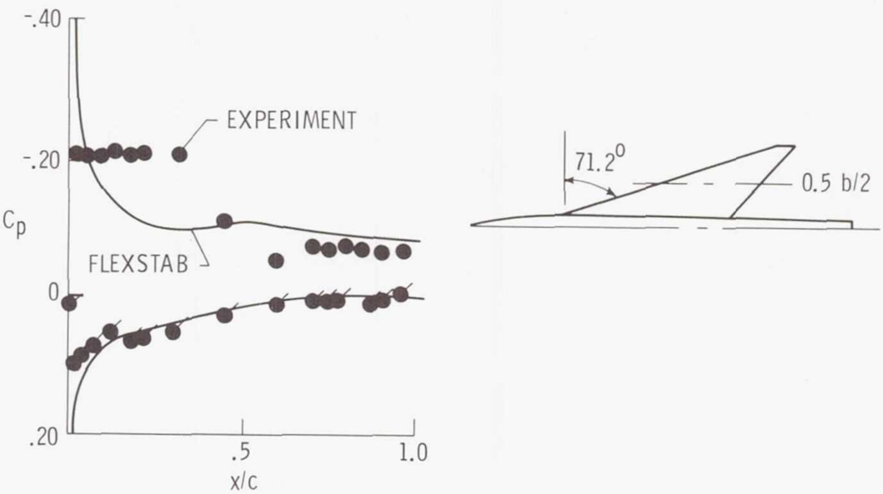


Figure 3.- Operating C_L for typical supersonic cruise aircraft.



(a) M = 0.85; C_L = 0.2.



(b) M = 1.70; C_L = 0.15.

Figure 4.- Effect of vortex flow on pressure distribution for structural design loads.

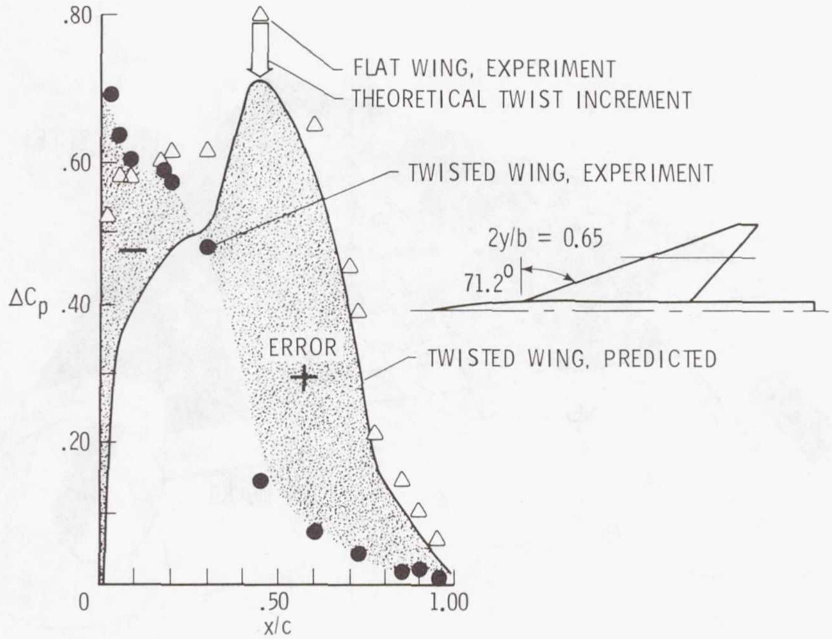


Figure 5.- Comparison of experiment and prediction for twist effects. $M = 0.85$; $\alpha = 8^o$; $\varepsilon_{tip} = -4.5^o$.

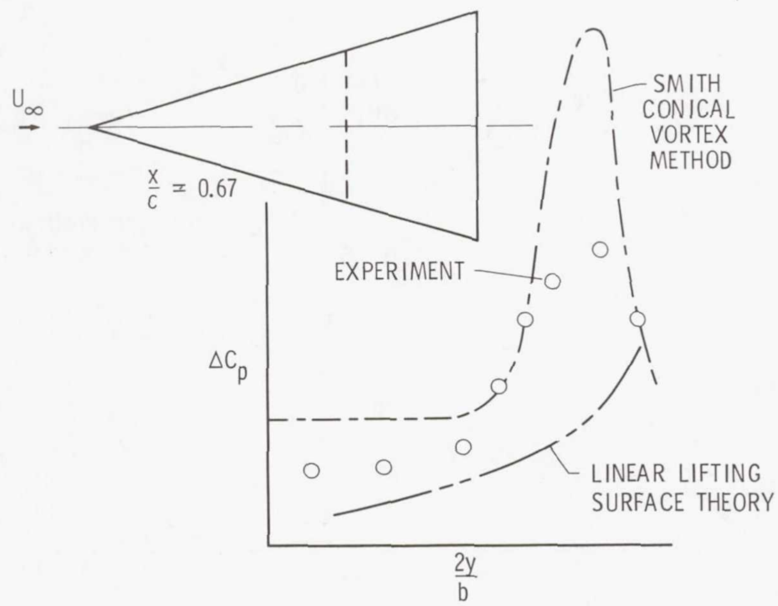


Figure 6.- Load distribution on delta wing given by earlier theories.

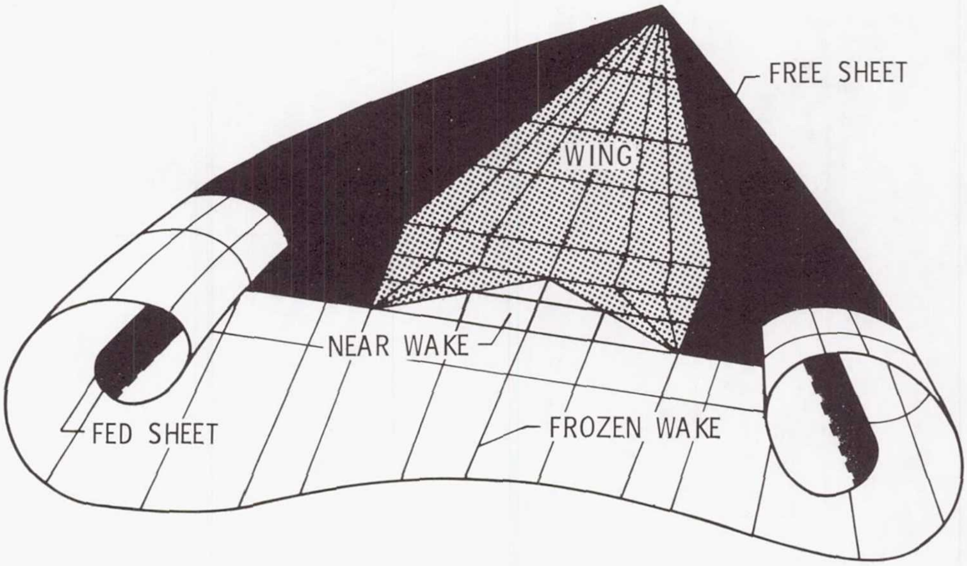


Figure 7.- Typical panel arrangement.

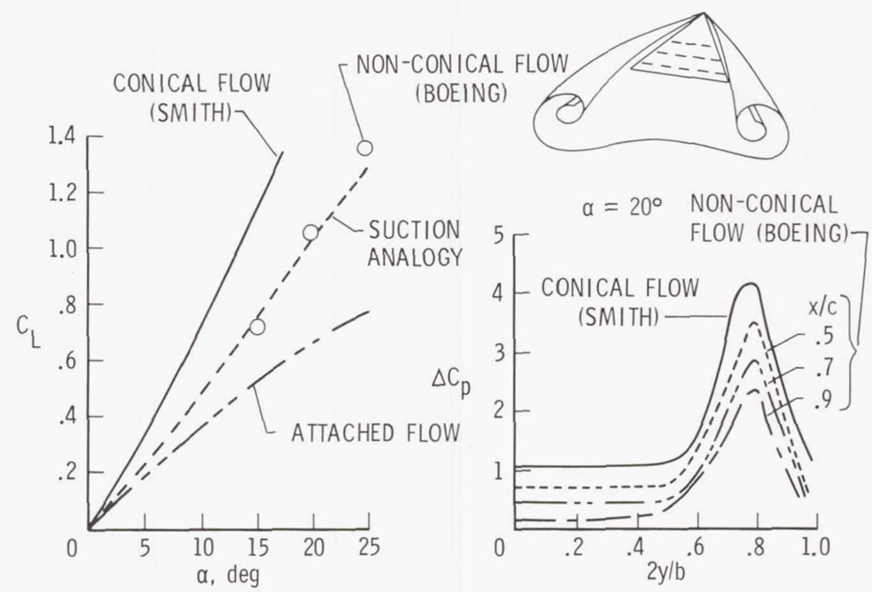


Figure 8.- Application of free vortex sheet method to slender wings. Aspect ratio of 2.

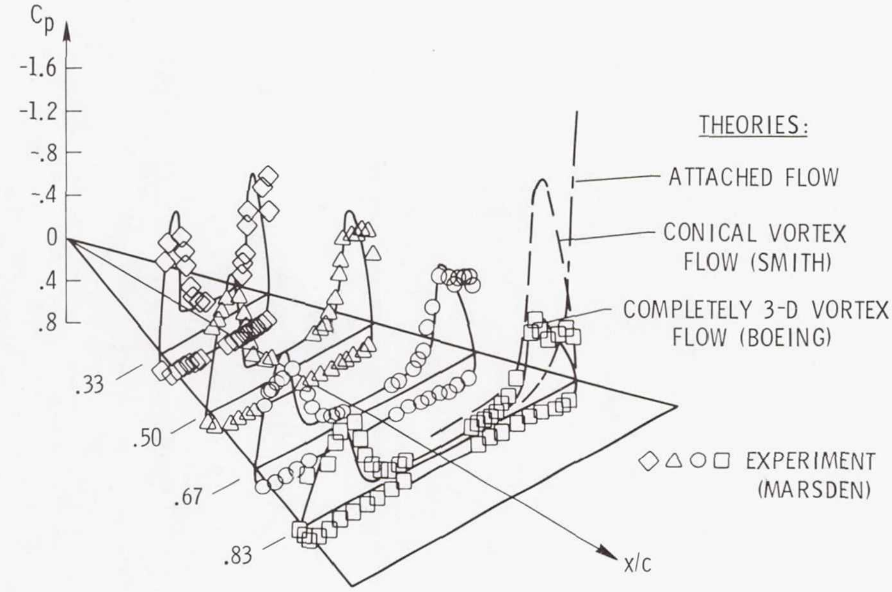


Figure 9.- Comparison of experimental (ref. 8) and theoretical surface loadings for a delta wing. Aspect ratio of 1.46; $\alpha = 14^{o}$; M = 0.

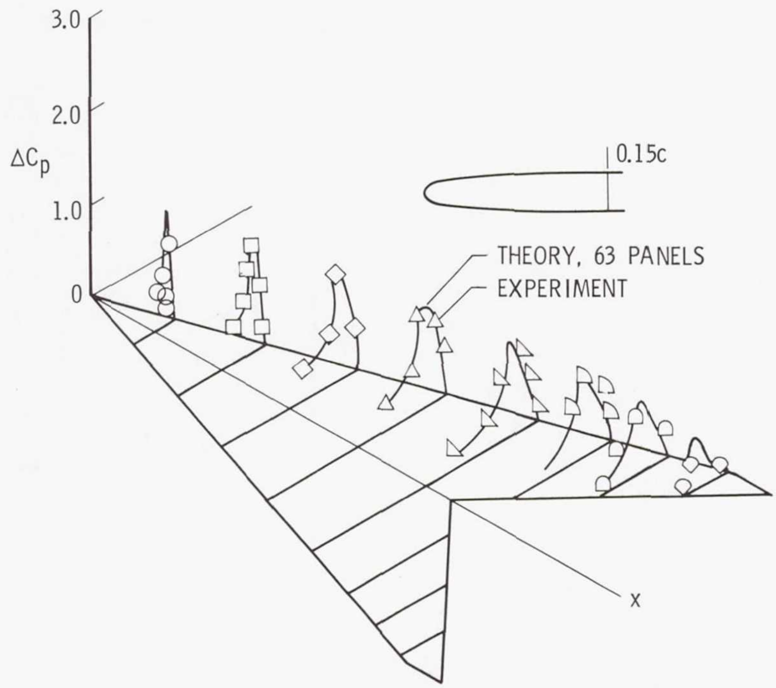


Figure 10.- Comparison of experimental (ref. 3) and theoretical surface loadings for an arrow wing with round leading edge. $\alpha = 11.9^{o}$; M = 0.40.