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UNSTEADY FLOW PAST WINGS HAVING SHARP-EDGE SEPARATION*

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SUMMARY

A vortex-lattice technique is developed to model unsteady, incompressible flow past thin wings. This technique predicts the shape of the wake as a function of time; thus, it is not restricted by planform, aspect ratio, or angle of attack as long as vortex bursting does not occur and the flow does not separate from the wing surface. Moreover, the technique can be applied to wings of arbitrary curvature undergoing general motion; thus, it can treat rigid-body motion, arbitrary wing deformation, gusts in the freestream, and periodic motions.

Numerical results are presented for low-aspect rectangular wings undergoing a constant-rate, rigid-body rotation about the trailing edge. The results for the unsteady motion are compared with those predicted by assuming quasi-steady motion. The present results exhibit hysteretic behavior.

INTRODUCTION

For steady flows there is ample experimental evidence indicating that flows past thin wings, even those exhibiting significant leading-edge and wing-tip separation, can be described by a velocity potential. We assume that the same is true for unsteady flow.

The velocity potential for incompressible unsteady flow is governed by Laplace's equation and is subject to the following boundary conditions:

(1) the fluid cannot penetrate the lifting surface,

(2) the disturbance created by the lifting surface must die out away from the surface and its wake,

(3) there must not be a discontinuity in the pressure in the wake, and

(4) the Kutta condition must be satisfied along the sharp edges when the flow is steady.

The present technique is an improvement over the previously developed techniques for treating this problem. For example, Morino and Kuo (ref. 1) developed a technique in which the integral equation governing the velocity potential

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is solved numerically. Ashley and Rodden (ref. 2), Rodden, Giesing and Kalman (ref. 3), Giesing, Kalman, and Rodden (ref. 4), and Albano and Rodden (ref. 5) developed techniques employing combinations of horseshoe-vortex lattice and doublets. However, these methods can treat small harmonic motions, and because none is capable of determining the geometry of the wake, the small harmonic motions must be about small angles of attack. Belotserkovskii (ref. 6) developed a technique for treating general unsteady motion, but because it is not capable of determining the geometry of the wake, it too is limited to small angles of attack. Djojodihardjo and Widnall (ref. 7) also developed a general technique in which the integral equation governing the velocity potential is solved numerically. Though they determined the geometry of the wake adjoining the trailing edge, they ignored the wing-tip vortex system; thus, their technique at best is limited to large angles of attack for moderately swept, high-aspect wings. With the present technique, the geometry of the wakes adjoining all sharp edges is determined as part of the solution, and there are no restrictions on the type of motion. The essential difference between the techniques of Belotserkovskii, Djojodihardjo and Widnall, and the present paper are illustrated in figure 1.

SYMBOLS

AR	aspect ratio
b	wing semi-span
C_n, C_m	normal-force, pitching-moment coefficients, respectively
C_p	pressure coefficient
C_r	root chord
$\vec{F}$	force vector
ℓ	length of vortex segment
$\vec{r}$	position vector
t	nondimensional time
Δt	time increment
$\vec{v}$	nondimensional velocity vector
X,Y,Z	wing-fixed coordinate system
α	angle of attack
α_o, α_f	initial and final angles of attack
Γ	nondimensional circulation
$\dot{\alpha}$	rate of change of angle of attack

THE PRESENT TECHNIQUE

For completeness, the vortex-lattice technique for steady flows is briefly discussed. Then the modifications needed to model unsteady flows are described.

Steady Flows

The wing surface is represented by a lattice of discrete vortex lines, while the wake is represented by a series of discrete nonintersecting vortex lines. Each vortex segment of the lattice is straight (the elemental areas are not necessarily planar), and each line in the wake is composed of a series of short straight segments and one semi-infinite segment. Control points are associated with each elemental area of the lattice and with each finite segment of the wake.

The desired velocity potential is the sum of the known freestream potential and the potentials of all the discrete vortex lines. The velocities generated by the latter are calculated in terms of the circulations around these segments according to the Biot-Savart law. These circulations are the primary unknowns.

To satisfy the no-penetration boundary condition, the normal component of the velocity is forced to vanish at each control point of the lattice. The velocity field generated by the vortex segments is calculated according to the Biot-Savart law; thus, the disturbance dies out far from the wing and its wake. The finite segments in the wake are aligned with the velocity at their control points in order to render the pressure continuous. Finally, no vortex segments on the lattice are placed between the last row and column of control points and the edge where the Kutta condition is imposed.

The problem is solved by the following iterative scheme:

(1) a direction is assigned to each segment in the wake,

(2) the circulations around each of the vortex segments are determined by simultaneously satisfying the no-penetration condition and spatial conservation of circulation,

(3) the segments in the wake are rendered force-free while the circulations are held constant,

(4) steps (2) and (3) are repeated until the shape of the wake doesn't change.

An example of a steady solution is shown in figure 2.

More details and results are given by Kandil, Mook and Nayfeh (ref. 8) and by Kandil (ref. 9).

Unsteady Flows

The initial condition can be a steady flow such as one obtained by the method described above or no flow at all. Here we consider the former. When conditions change with time, starting vortices form along the sharp edges; then they are shed and convected downstream with the local particle velocity. Thus, an ever-growing portion of the wake must also be represented by a lattice, not a series of nonintersecting lines as in the steady case. This is the essential difference between the steady and the unsteady model.

The continuous variation with time is approximated by considering the motion to be a series of impulsive changes occuring at evenly spaced time intervals; thus, the motion becomes smoother as the time intervals become smaller.

In figure 3, the wake adjoining the wing tip and trailing edge is spread out to illustrate how the lattice forms in the wake. The first arrangement shows the initial conditions; this corresponds to a steady solution such as the one shown in figure 2. The next arrangement corresponds to time = 1; hence, there is one shed vortex line in the wake. The last arrangement shown corresponds to time = 2. An actual solution is shown in figure 4; this picture corresponds to time = 4.

With an incompressible model of the flow, the instant the angle of attack changes, the vorticity on the wing and the position of the entire wake (i.e., the direction of the vorticity in the wake) change. A starting vortex forms along the sharp edges and subsequently is shed. But the strength of the vorticity in the wake does not change because the vorticity is convected downstream with the fluid particles. Such a model of the flow is realistic only when the particle velocity is small compared with the speed of sound (i.e., when the Mach number is small).

In terms of the present discrete-line representation, the instant the angle of attack changes, the circulations in the lattice representing the surface and the directions of the finite segments representing the wake change. But the circulations around the finite segments in the wake do not.

One cannot, simultaneously, render the wake force-free, satisfy the no-penetration condition on the surface, and spatially conserve circulation unless one adds a new vortex line which essentially parallels the sharp edges. Thus, the Kutta condition cannot be imposed during unsteady motion. This new vortex line represents the shed vorticity which is convected downstream causing a lattice to form in the wake. One new vortex line is formed for each time interval. When the wing stops rotating, lines continue to be shed; however, the strengths of these lines decrease and the steady-state results are approached rapidly. This is illustrated in figures 5 - 7. The sequence of events leading up to figures 5 - 7 is as follows: Initially the angle of attack was eleven degrees and the flow was steady. Then the angle of attack was increased at the rate of one degree per nondimensional time unit until the angle of attack reached fifteen degrees. At this point the angle of attack stopped changing. The general unsteady program was allowed to run for twelve time units. This allowed the strength of the shed vortices to vanish, those of appreciable strength to be convected far downstream, and the flow to achieve a steady state.

In all three cases, the lift and moment produced by the unsteady flow are lower than those produced by a steady flow at the same angle of attack. The steady-flow results are shown by the dotted lines.

At each time step, the solution is obtained in essentially the same way that the steady problem is solved. But now there is the added complication of convecting the shed vorticity downstream with the particle velocity. This is accomplished by moving the ends of the segments of the shed line according to

$$\vec{r}(t + \Delta t) = \vec{r}(t) + \vec{v}\Delta t$$

where $\vec{v}$ is the particle velocity and Δt is the time interval.

The nondimensional loads are calculated according to

$$\vec{F} = 2\ell\vec{\Gamma} \times \vec{v}$$

where ℓ is the nondimensional length of the segment on which the force $\vec{F}$ acts, $\vec{\Gamma}$ is the circulation around this segment multiplied by a unit vector parallel to the segment and $\vec{v}$ is the velocity at the midpoint of the segment. The resultant force is obtained by adding the forces on the bound segments. The pressures are calculated by averaging one-half the forces on the segments along the edges of an elemental area over the elemental area, exceptions being those elements along the leading edge for which the entire force acting on the forward segment is averaged.

Figure 8 shows the convergence as the number of elements is increased. Comparing figures 9 and 10 with figures 5 and 6 shows that the unsteady results approach the steady results as the rate of changing the angle of attack decreases.

Figures 11 and 12, which show hysteretic behavior, compare the results for increasing angle of attack, decreasing angle of attack, and the steady state. The initial conditions are the steady-state solutions at eleven and fifteen degrees.

More details and results are given by Atta (ref. 10).

CONCLUDING REMARKS

The method presented here is general. It can be used to treat arbitrary motions, including harmonic oscillations. And it can be used to treat leading-edge separation.

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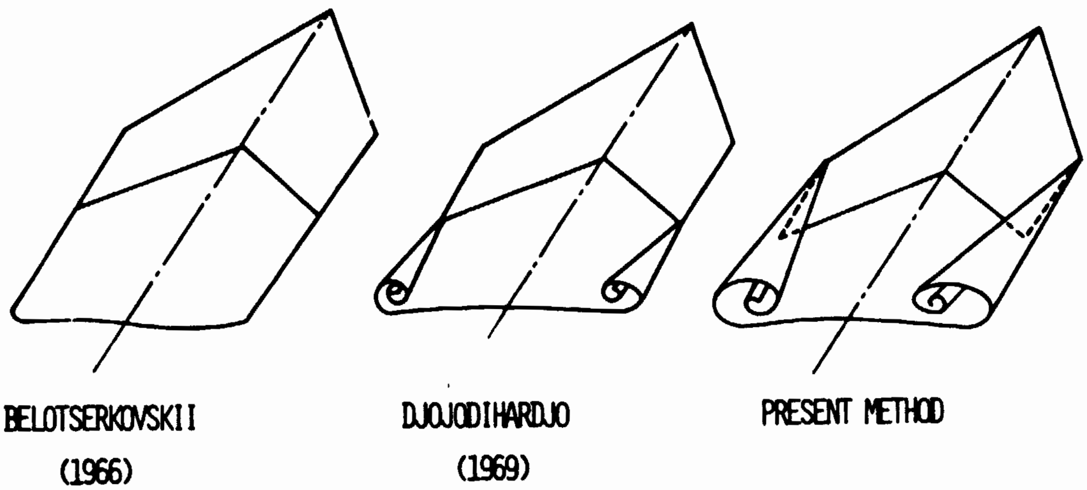

Figure 1.- Comparison of different methods.

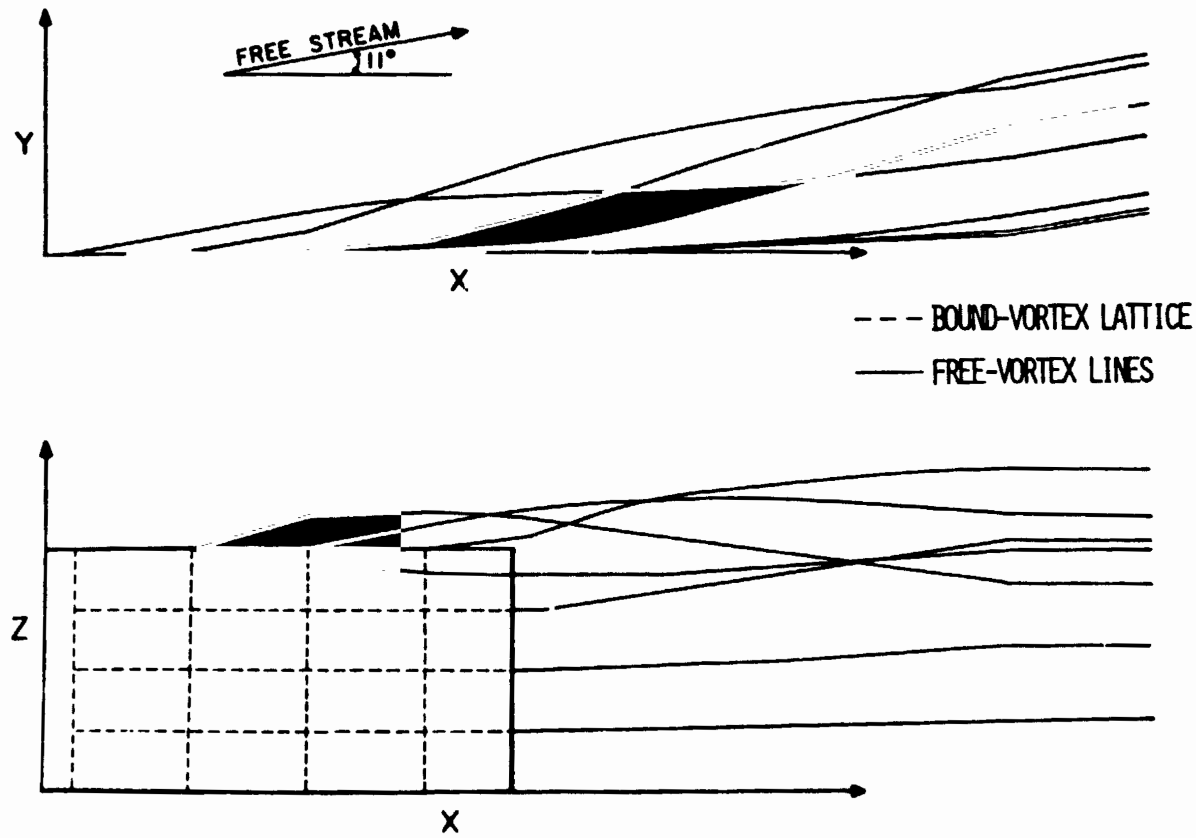

Figure 2.- Wake shape in a steady flow. $\alpha = 11^{o}$; AR = 1.

(WING-TIP VORTICES ARE ROTATED 90° FOR DEMONSTRATION)

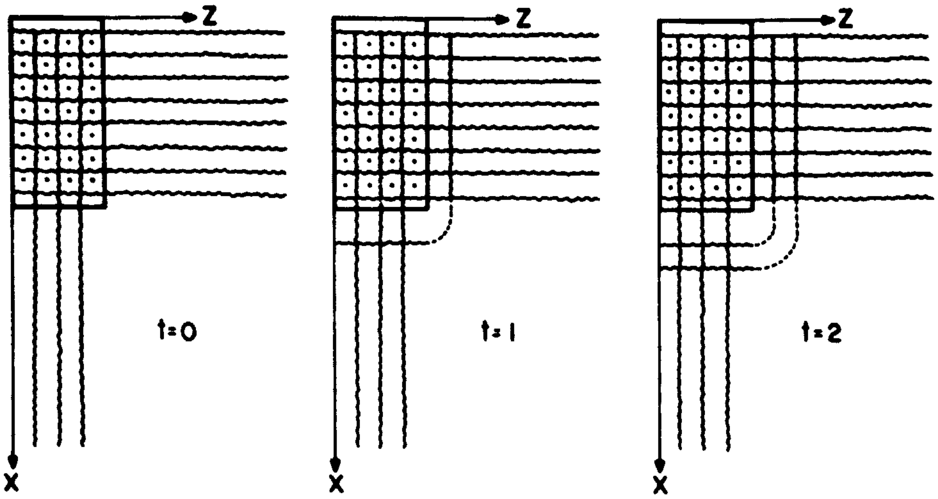

Figure 3.- Shed-vortex lines.

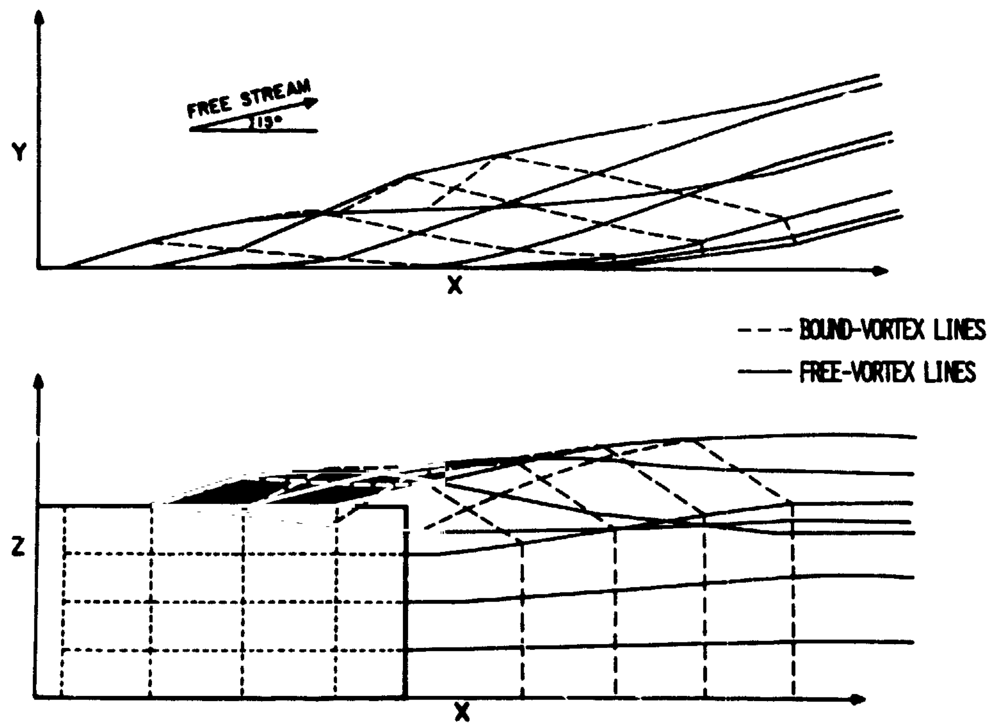

Figure 4.- Wake shape in an unsteady flow. $\alpha_o = 11^\circ$; $\alpha_f = 15^\circ$; $\dot{\alpha} = 1$; AR = 1; t = 4.

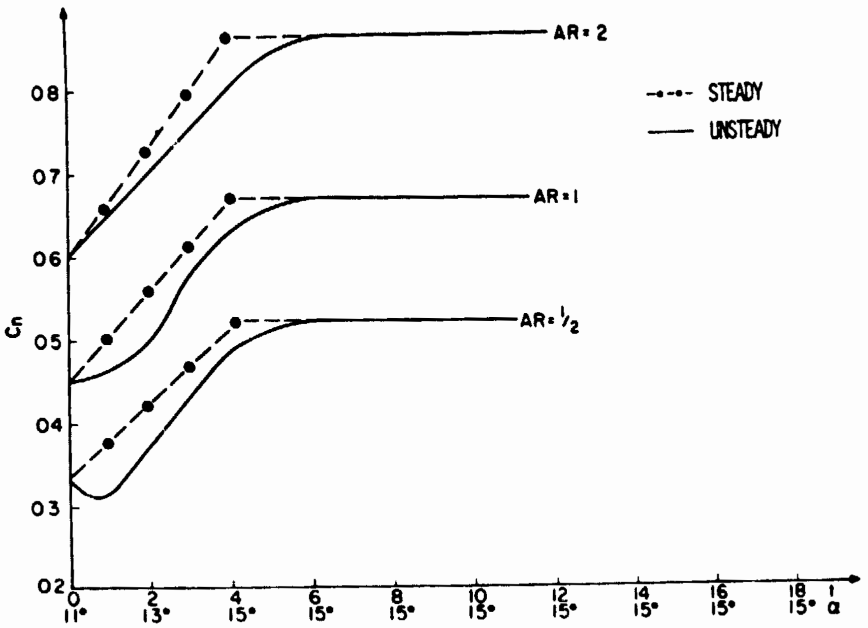

Figure 5.- Variation of the normal-force coefficient.
$\alpha_o = 11^o$; $\alpha_f = 15^o$; $\dot{\alpha} = 1$; $\Delta t = 1$.

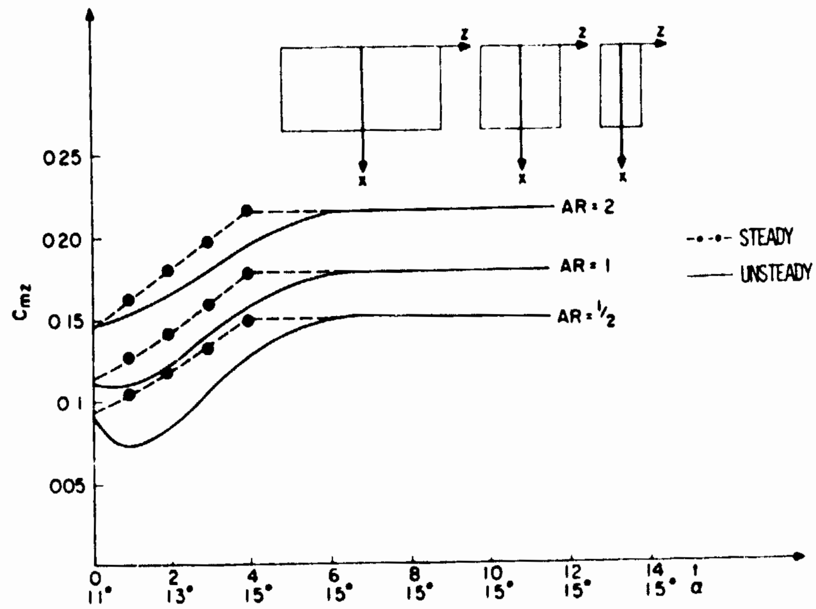

Figure 6.- Variation of the pitching-moment coefficient.
$\alpha_o = 11^o$; $\alpha_f = 15^o$; $\dot{\alpha} = 1$; $\Delta t = 1$.

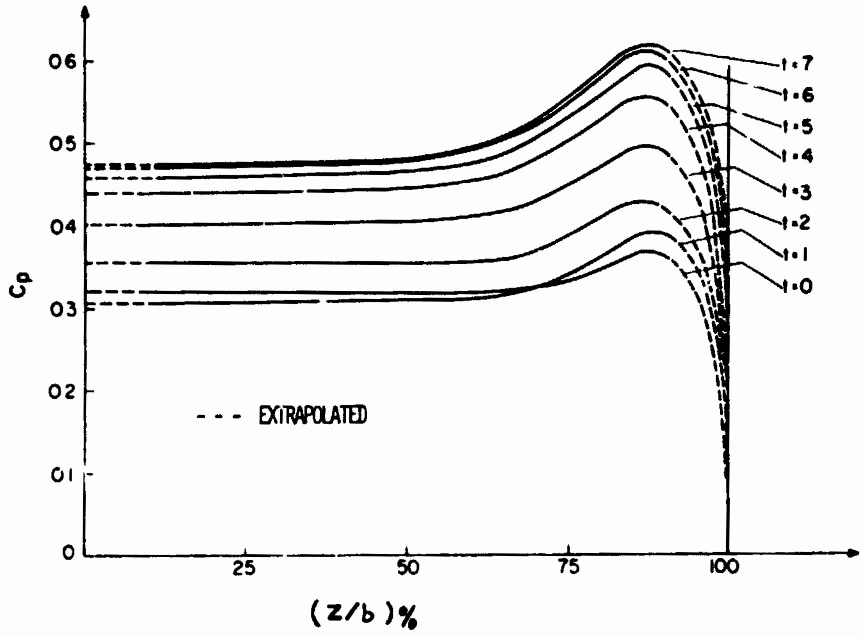

Figure 7.- Pressure coefficient variation. $\alpha_o = 11^o$; $\alpha_f = 15^o$; $\dot{\alpha} = 1$; AR = 1; $\Delta t = 1$; $X/C_r = 43.75\%$.

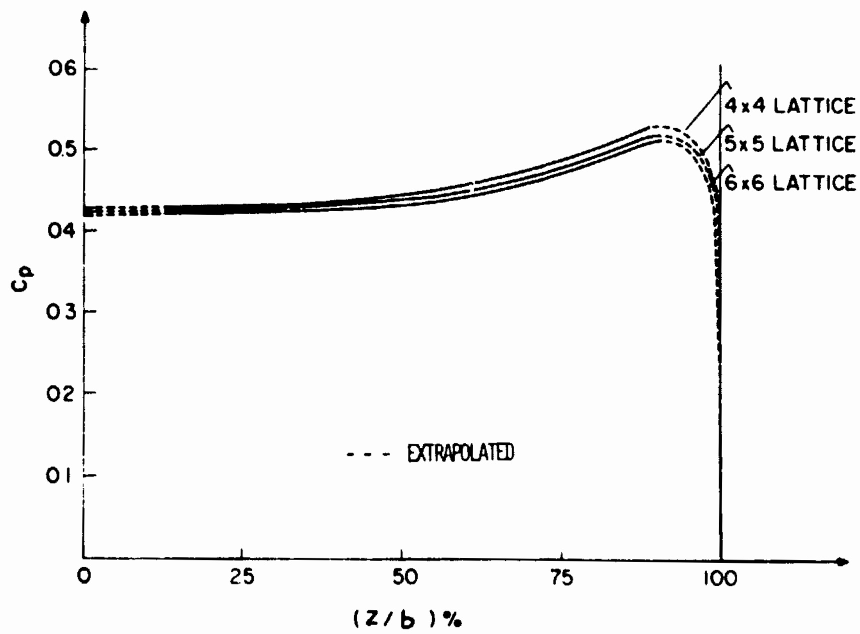

Figure 8.- Pressure coefficient for different lattices. $\alpha_o = 11^o$; $\alpha_f = 15^o$; $\dot{\alpha} = 1$; AR = 1; $\Delta t = 1$; $X/C_r = 43.75\%$; t = 5.

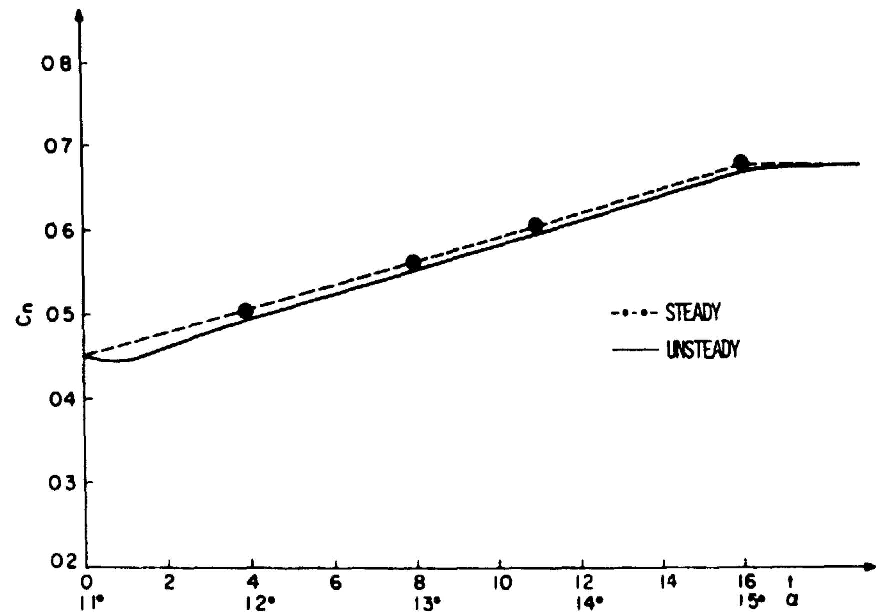

Figure 9.- Quasi-steady variation of the normal-force coefficient. $\alpha_o = 11^o$; $\alpha_f = 15^o$; $\dot{\alpha} = 0.25$, $\Delta t = 1$; AR = 1.

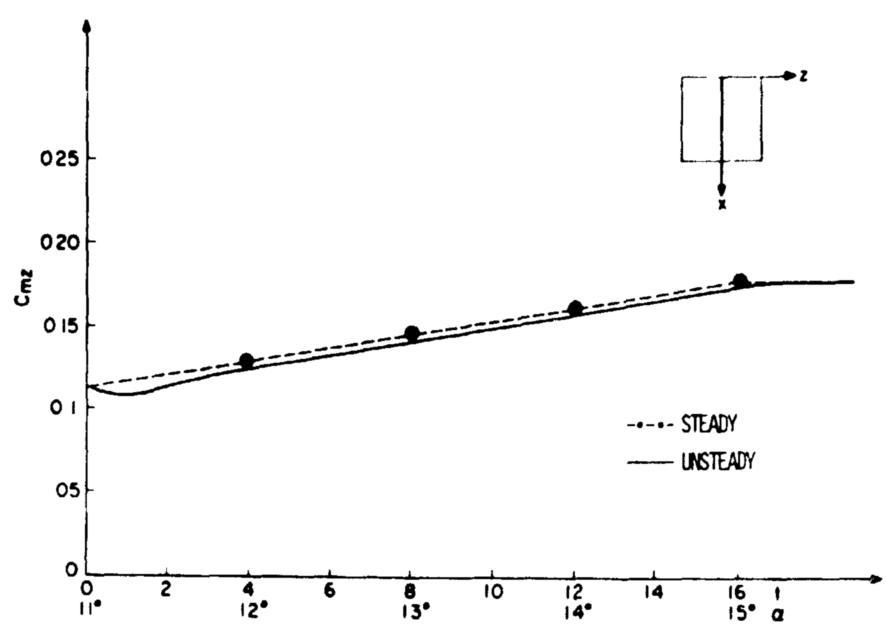

Figure 10.- Quasi-steady variation of the pitching-moment coefficient. $\alpha_o = 11^o$; $\alpha_f = 15^o$; $\dot{\alpha} = 0.25$; $\Delta t = 1$; AR = 1.

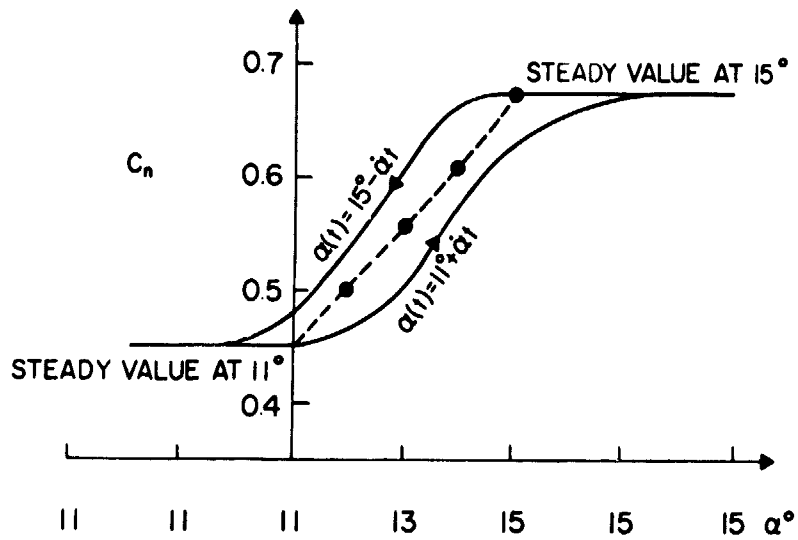

Figure 11.- Normal-force coefficient.

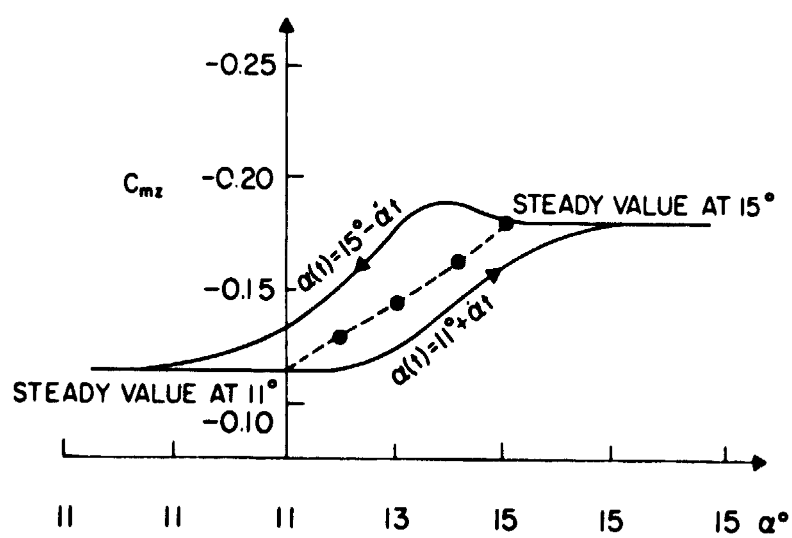

Figure 12.- Pitching-moment coefficient.

SUMMARY OF OPEN DISCUSSION ON FUTURE VORTEX-LATTICE UTILIZATION

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The response of the attendees during the open discussion on vortex-lattice utilization was excellent. The intent of this summary is not to evaluate the comments made but simply to indicate the topics discussed. Essentially, the discussion focused on the following general topics: grid layout, drag calculations, bodies in combination, vortex lift, and separated flow effects.

In order to stimulate and initiate the discussion, a panel was set up on a spur-of-the-moment basis. Members were Jan Tulinius of NASA Langley Research Center, Joseph Giesing of McDonnell Aircraft Company, Winfried Feifel of The Boeing Company, and Brian Maskew of Analytical Methods, Inc. The subjects covered by each of these members are essentially as follows:

Tulinius, in effect, gave a very good impromptu paper. He covered two-dimensional and three-dimensional drag effects and discussed the equivalence of near- and far-field drag estimates. He mentioned supersonic vortex-lattice methods and pointed out problems associated with Mach cone and sonic line singularities, with natural edge conditions, and with nonplanar effects. He also discussed the use of distributed singularities versus the use of lattice constraint functions. Also covered was the topic of free vortices, whether of the leading-edge variety for arbitrary planforms or as associated with trailing-edge and tip wakes.

Giesing's remarks also constituted a very good impromptu paper. He discussed areas for numerical improvement of the lattice method with topic coverage as follows:

Supersonic flow

Infinite velocity on Mach cones
Smearing of loads - loads wandering out of Mach cone
Instability of solutions

Convecting singularities (jets, wakes, leading-edge vortices)

Infinite velocity when vortex contacts control point
Force or pressure calculation inconvenient on yawed elements
Wake next to fuselage
Low lift for jet flaps

Subsonic flow

Discontinuity in Δx causes disturbance in pressures
Collocating points on body surfaces, while using axial singularities can cause instabilities
High frequency lattice method expensive and/or inaccurate
Computing time and accuracy trade-off for wing-bodies

Areas where Giesing felt there was need for basic improvement in the lattice methods are as follows:

Transonic flow

Empirical corrections

Viscous corrections

Steady
Unsteady

Oscillatory flow

Nonplanar flaps down, etc.
Wing-jet interaction (compressible)
Leading-edge vortex

Lateral-directional forces

Feifel emphasized the need for practical considerations and input simplicity. He discussed problems related to the treatment of cambered wings. He also felt more attention should be given to grid system layout, especially with respect to the simulation of bodies or other complex configurations. The treatment of high lift configurations, such as constant chord flaps on tapered wings, and the situation of wings with cutouts also represent problem areas.

Maskew's comments are summarized as follows. He referred to the use of constraint functions discussed by Tulinius as a possible alternative to the subvortex technique for keeping the number of unknowns down while effectively using a large number of vortices. Maskew mentioned that he had used constraint functions with a subvortex model, as reported in NASA TM X-73115 (ref. 1). The number of unknowns was halved without spoiling the pressure calculations at the arbitrary points. With the small number of unknowns, i.e., 46, the savings in solution time was about the same as the time required to manipulate the matrix. For a larger number of unknowns, there should be a savings in computer time. On the question posed by Houbolt on separated flow modeling, Maskew felt the answer might be found in Giesing's comments, namely, that the multienergy modeling developed by Shollenberger for jet flow interference might also be adapted for the low energy region associated with separated flows. Maskew mentioned that certain problems arise in wake rollup calculations of complicated flap systems. For the 747 flap system, with edge vortices on each flap, he found that the two opposing regions from the flap edges adjacent to the high-speed aileron pose a problem in that the calculations predict an orbiting motion which does not appear in real flow. The two vortices in fact soon cancel each other, leaving a single wake vortex. This merging problem needs further investigation so that it can be modeled correctly. Another problem he discussed deals with the near-field calculation of forces using the Kutta-Joukowski law applied to vortex segments. He pointed out that in most cases the forces are calculated only on the bound vortex segments, and with the assumption that the chordwise segments are alined with the local mean velocity and therefore carry no load. In some configurations this assumption is not valid. He brought out the example of a yawed wing which has been paneled for symmetrical flow and raised the question, does the wing need repaneling before calculating the yawed condition. The problem also appears on wings with deflected flaps. Large mean spanwise flow components exist on the flaps, particularly near the tip, and if the forces on the chordwise segments are computed in this case, the Kutta trailing-edge condition appears violated. Maskew pointed out that this problem requires further attention and that perhaps the chordwise segments should always be alined with the mean flow direction.

In summary, the following items appear to be of chief concern in continuing and future development of the vortex-lattice methods:

1. Grid layout, especially with respect to the use of the 1/4-point, 3/4-point rule, or the approach which employs equal angular spacing within a semicircle

2. Drag calculation techniques

3. Bodies in combination

4. Separated flow effects including wake rollup

5. Supersonic flow applications

6. Treatment of lateral flow or of combined pitch and yaw displacement

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