Engineering Notes

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Analytical Investigation of Aerodynamic Characteristics of Highly Swept Wings with Separated Flow

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Nomenclature

A	= aspect ratio
$b(x)$	= local wing span
$\bar{c}$	= mean aerodynamic chord
C_L	= lift coefficient
C_m	= pitching moment coefficient
FVS	= free vortex sheet
M	= Mach number
QVL	= quasi-vortex lattice
VLM-SA	= vortex-lattice method with suction analogy
x,y,z	= body axis coordinates
α	= angle of attack
ΔC_D	= drag-due-to-lift coefficient
ΔC_p	= difference between upper and lower surface pressure coefficients

Introduction

MANY modern aircraft designed for supersonic speeds employ highly swept-back and low-aspect ratio wings with sharp or thin edges. Flow separation occurs near the leading and tip edges of such wings at moderate to high angles of attack. The separation produces vortex sheets that roll up into strong vortices above the wing surface. These vortices, which are regions of low pressure, generate additional lift which is responsible for the well-known nonlinear aerodynamic characteristics.

In the design of high-speed aircraft, a detailed knowledge of separation-induced vortex flow is needed to predict the performance under various operating conditions. As the attached flow theories are inadequate for these conditions, the designer has to rely presently on extensive and costly wind tunnel tests for the required data. Therefore, attempts have been made over the years to develop analytical methods for predicting the aerodynamic characteristics of such aircraft. They have met with varying degrees of success. A brief summary of some of the more successful methods is given in the next section. Before any method can really be useful, it has to be tested against a standard set of data to determine its capabilities and limitations. In this work, such an investigation is undertaken. Both flat and cambered wings of different configurations for which experimental data is available are studied and comparisons made.

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Analytical Methods

In this section the methods employed in the present study are briefly described.

1) The free-vortex-sheet (FVS) method,[1] developed by Boeing Aircraft Company under a contract with NASA Langley Research Center, is based on a three-dimensional inviscid flow model. This is an advanced panel method using distributed doublet singularities located on the mean surface of the wing and free vortex sheet. It is capable of computing forces, moments, and surface pressures.

2) The vortex-lattice method with suction analogy (VLM-SA)[2] developed at Langley Research Center estimates overall forces and moments of complex planforms. However, it does not provide a detailed surface pressure distribution. The complex planforms include wings with variable sweep, changes in dihedral angle across the span, twist and/or camber, and also wings in conjunction with a tail or a canard. The method is based on steady inviscid flow and represents the lifting surfaces with the vortex lattice.

3) The quasi-vortex lattice (QVL) method of Mehrotra[3] predicts the aerodynamic characteristics, both pressures and integrated results, of low-aspect ratio wings with partial leading edge separation in a steady inviscid flow. Here the wing is represented by a bound vortex sheet, across which there is a pressure differential, and the separated flow along the leading edge by a force-free vortex sheet. The trailing wake is also free. The method uses an iterative procedure.

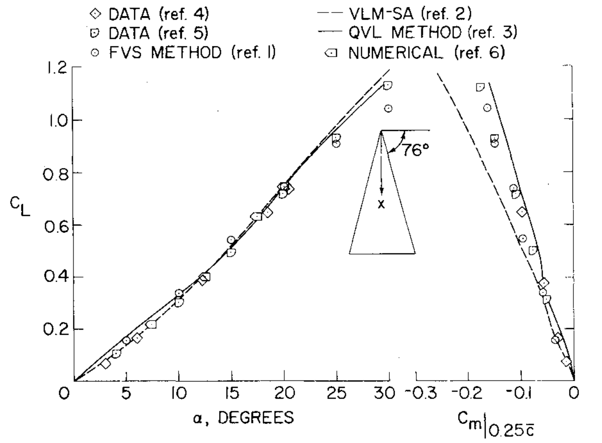

Fig. 1 Longitudinal aerodynamic characteristics of $A = 1$ delta wing; $M \simeq 0$.

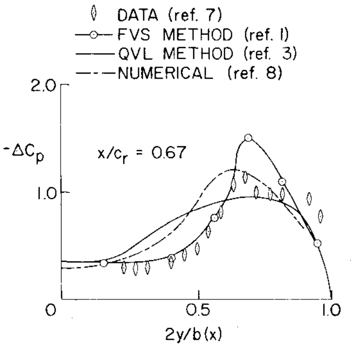

Fig. 2 Spanwise pressure distribution for $A = 1.46$ delta wing; 14 deg; $\Omega \simeq 0$.

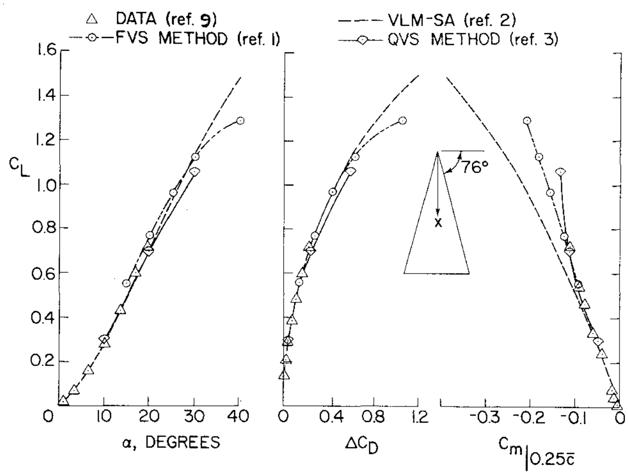

Fig. 3 Longitudinal aerodynamic characteristics of $A = 1$ Squire's spanwise cambered delta wing-2; $M \simeq 0$.

Results and Discussion

Flat Wings

The lift and pitching moment coefficients for an $A = 1$ delta wing are shown in Fig. 1. The results obtained by using the FVS, QVL, and VLM-SA methods are compared with the experimental values of Peckham[4] and Tosti,[5] and also with the numerical results of Kandil et al.[6] over an angle-of-attack range of 0-30 deg. There is a fairly good agreement for lift coefficient between the data and all of the theoretical results over most of the investigated range of angle of attack. However, at higher angles of attack, the FVS method underpredicts, the VLM-SA overpredicts, and the QVL method is in close agreement with the data for C_L. The pitching moment coefficient by the FVS and QVL methods agrees more favorably with the data than that by VLM-SA method, especially at higher angles of attack.

The spanwise pressure distribution for a delta wing of aspect ratio 1.46 is shown in Fig. 2. The FVS method gives a pressure distribution which is in better agreement with the data of Marsden et al.[7] than that by the QVL method or numerical method of Kandil et al.[8] However, the peak values of ΔC_p given by the FVS method are greater than either the data or those given by the other methods; this is indicative of the equivalent vortex core representation in the FVS method.

Cambered Wings

Figure 3 compares the longitudinal aerodynamic characteristics obtained by the three methods with the experimental values of Squire[9] for a spanwise cambered delta wing. The data are available for an angle-of-attack range of 0-20 deg. The agreement between the theories and the data is good. However, the FVS method could not handle large cambered wings whereas the other methods could (Squire's wings 5 to 7).

Conclusions

All three analytical methods successfully predict the aerodynamic characteristics of low-aspect ratio wings up to moderate angles of attack. However, they generally overpredict the pitching moment. No firm conclusions could be drawn regarding their capabilities at higher angles of attack because of insufficient data. More investigation is needed in this respect.

The FVS method is more sophisticated, but seems to be incapable of handling wings with large camber. It requires comparatively large computational time and input data. It predicts better surface pressure distributions. The QVL method can model low-aspect ratio, arrow, delta, and diamond wings, but more study is required before it can be used conveniently for arrow and diamong wings. It needs the least amount of input data and provides net pressure acting on the wing—unlike the FVS method, which gives upper and lower surface pressures. The VLM-SA method can handle complex planforms. It predicts results which are considerably greater than those given by the other methods at higher angles of attack. It takes the least amount of computational time, but does not give the detailed surface load distribution.

Acknowledgment

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