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November 1969

A COMPARISON OF EXPERIMENTAL AND THEORETICAL AERODYNAMIC COEFFICIENTS FOR TWO ASYMMETRICAL REENTRY VEHICLES (U)

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Sandia Laboratories, Albuquerque

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ABSTRACT (U)

Experimental and theoretical values of axial force and pitching moment coefficients for two asymmetrical reentry vehicles are presented in graphical form.

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SUMMARY

Theoretical predictions of static stability and resulting trim angle of attack for bent and warped reentry vehicles and axial force coefficients are compared with experimental results.

It is concluded that aerodynamic coefficients for vehicles within the limits of this study may be theoretically determined to a degree of accuracy adequate for flight dynamics analysis.

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LIST OF SYMBOLS

A	Reference area, in.^{2}
C_A	Axial force coefficient, axial force/$q_\infty A$
C_m	Pitching moment coefficient, pitching moment/$q_\infty Ad$
C_p	Pressure coefficient, $(P - P_\infty)/q_\infty$
d	Reference diameter, in.
L	Undamaged vehicle length, in.
M_ℓ	Local Mach number
M_{ns}	Mach number normal to shock wave
M_∞	Free stream Mach number
P_o	Tunnel stilling chamber pressure, lb/in.^{2}
P_ℓ	Local pressure, lb/in.^{2}
P_∞	Free stream pressure, lb/in.^{2}
q_∞	Free stream dynamic pressure, lb/in.^{2}
T_o	Tunnel stilling chamber temperature, °R
X	Axial distance downstream of vehicle nose, in.
α	Angle of attack, pitch plane, deg
δ	Distortion of warped vehicle centerline from undamaged vehicle centerline, in.
ϕ	Model roll angle, deg
θ	Angle between body and free stream velocity, deg
γ	Ratio of specific heats

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A COMPARISON OF EXPERIMENTAL AND THEORETICAL AERODYNAMIC COEFFICIENTS FOR TWO ASYMMETRICAL REENTRY VEHICLES

Introduction

Uneven ablation, vehicle structural failure, and uneven vehicle heating often lead to geometrical distortions in reentry vehicles (RV's) (References 1 and 2). These distortions in vehicle geometry may be great enough to cause a considerable change in the aerodynamic coefficients of the vehicle. These changes include center-of-gravity offsets and trim angles of attack.

As noted in References 1 and 2, these aerodynamic asymmetries often lead to RV spin up and/or roll reversal. Thus, a study was undertaken to determine if the theoretical tools presently available are capable of adequately predicting the aerodynamics of these asymmetrical vehicles for flight dynamics analysis.

The experimental results used for this study were obtained from Reference 3. This experimental program, conducted by the General Electric Company, consisted of wind tunnel tests of a sleighride RV and several damaged configurations.

Theoretical calculations were made, using the Douglas Hypersonic Arbitrary Body Computer Program (Reference 4).

Theoretical Analysis

Shown in Figure 1 are the geometrical details of the models which were studied. In order to theoretically analyze the models, it was necessary to divide them into many small rectangles. Computer drawings of these resultant models are shown in Figures 2, 3, and 4. Test conditions and reference values are listed in Table I.

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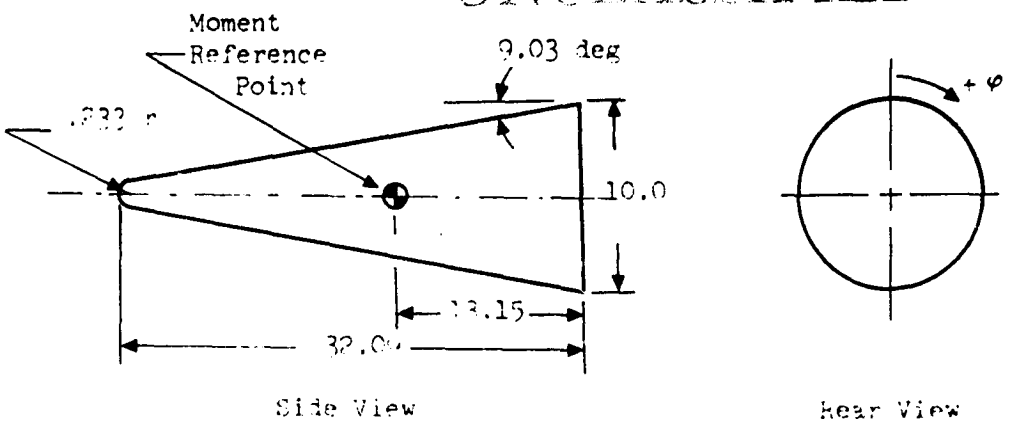

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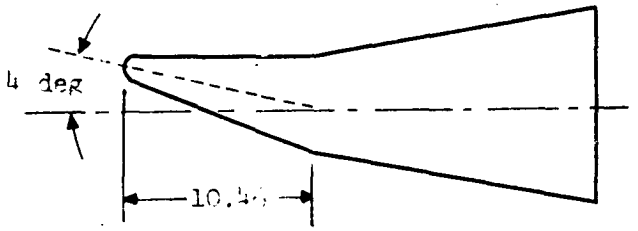
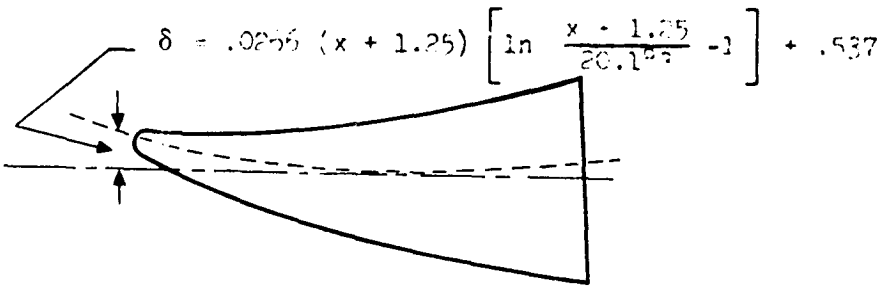


(b) Bent-Nose Configuration



(c) Warped Configuration

Figure 1. Model Details

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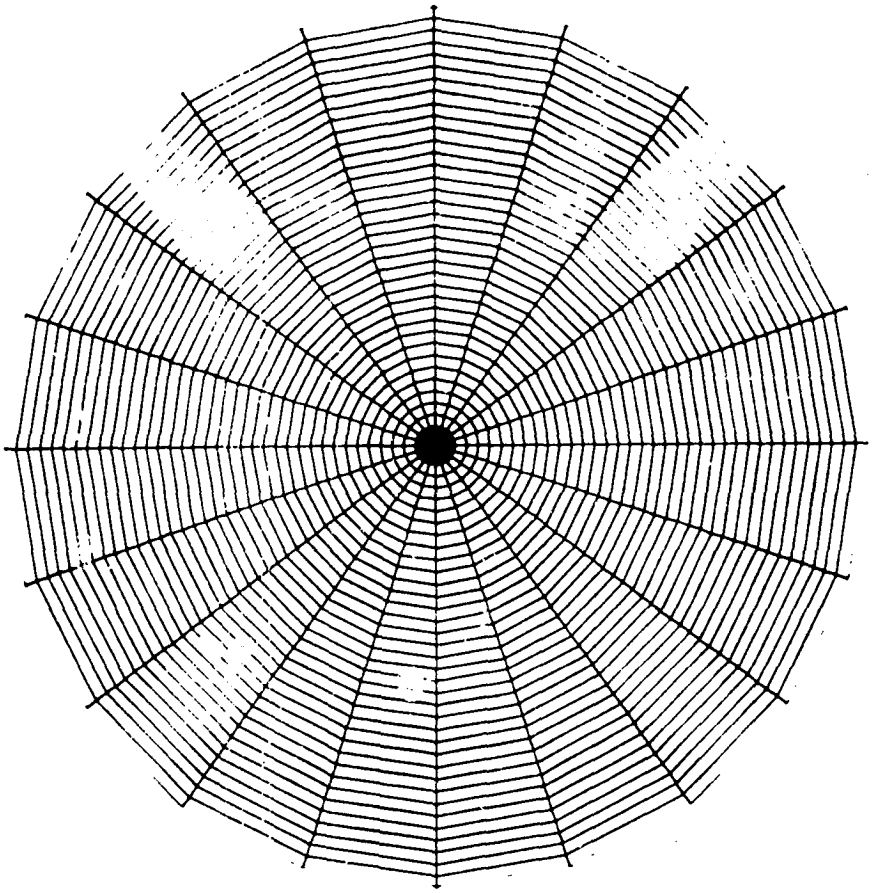

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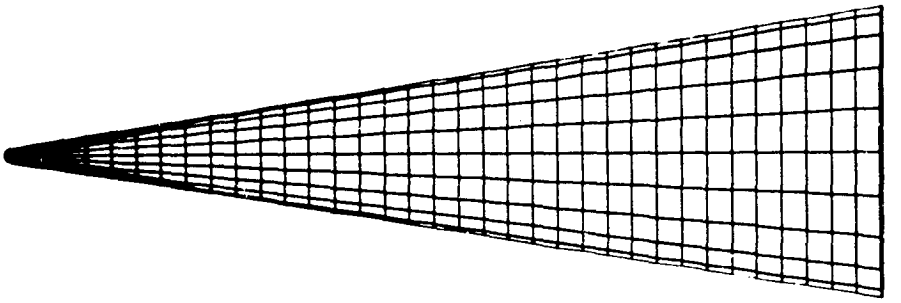

(b) Side View

Figure 2. Theoretical Model - Undamaged Configuration

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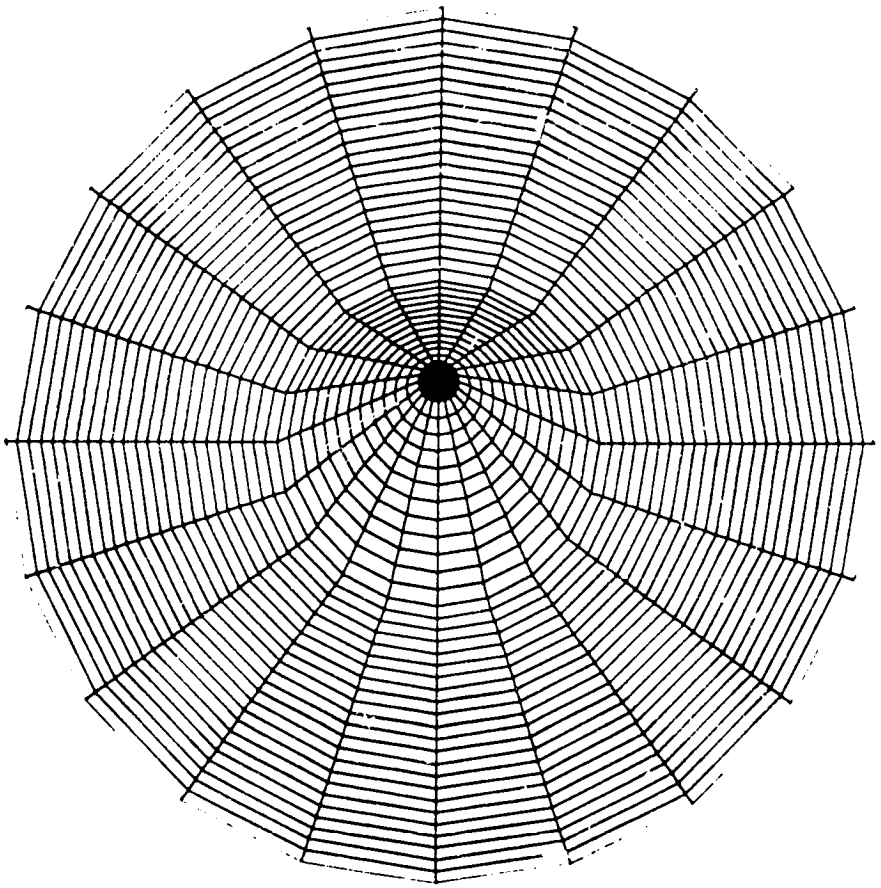
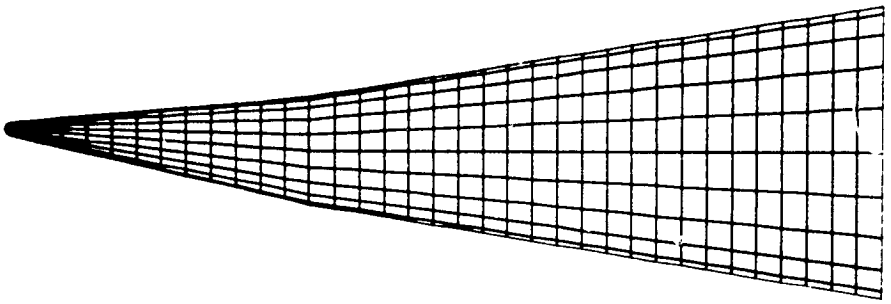


(a) Front View



(b) Side View

Figure 3. Theoretical Model - Bent Nose Configuration

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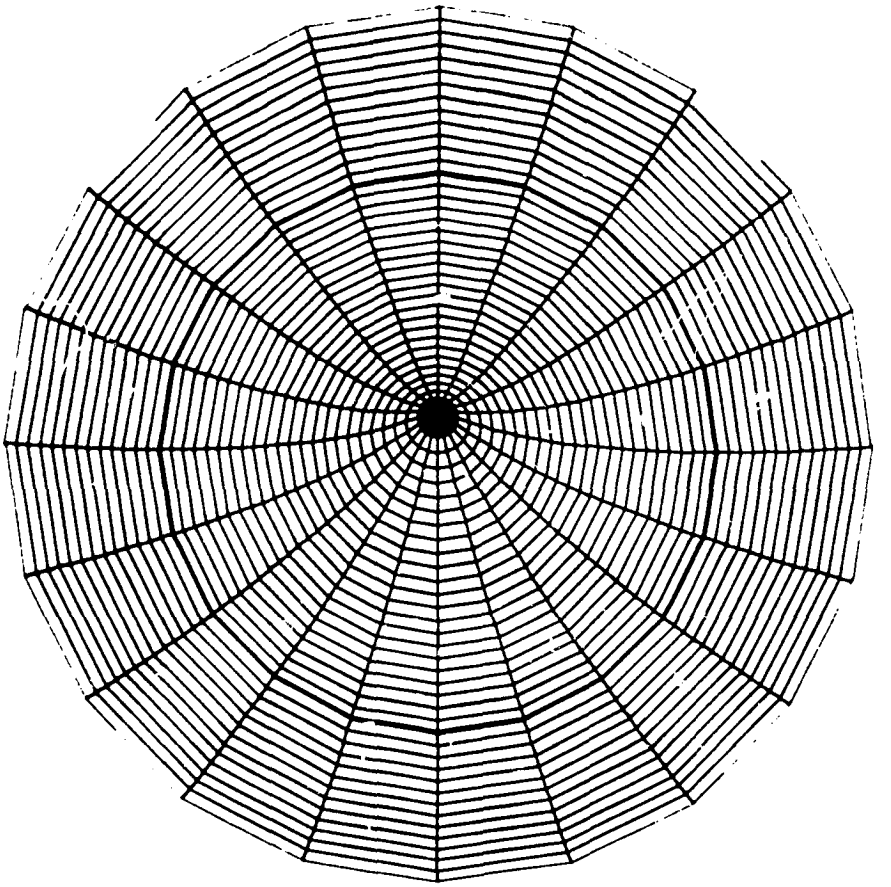
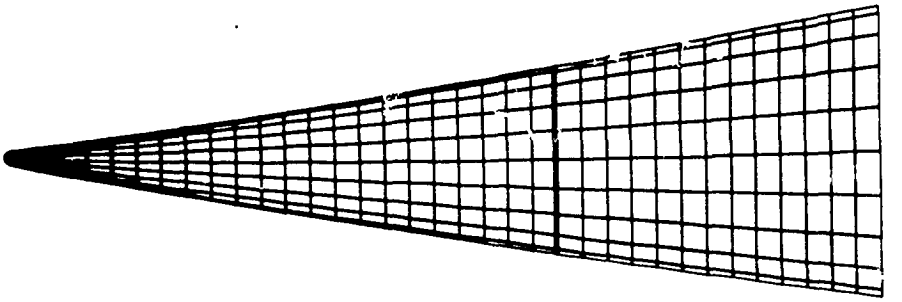


(a) Front View



(b) Side View

Figure 4. Theoretical Model - Warped Configuration

TABLE I

Test Conditions and Reference Values

M_∞	P_o (lb/in.^{2})	T_o (°R)	q_∞ (lb/in.^{2})	ϕ (deg)	A_2 (in.^{2})	d (in.)	L (in.)
10.15	1725	1900	2.6	0.0	78.54	10.0	32.09

Several different theoretical methods were used on different portions of the body. The theoretical methods used on various portions of the body were:

	Impact Theory	Shadow Theory
Nose (x = 0.0 to 0.196)	Modified Newtonian	Prandtl-Meyer
Afterbody (x = 0.0196 to 32.09)	Tangent cone	Prandtl-Meyer
Base	Modified Newtonian	High mach number base pressure

A brief description of these theories is given below.

Modified Newtonian

The usual form of the modified Newtonian pressure coefficient is:

$$C_p = K \sin^2 \theta \ , \tag{1}$$

where θ is the angle between the free stream velocity vector and the vector normal to the surface of the body.

In true Newtonian flow ($M = \infty$, $\gamma = 1$), the parameter K is taken as 2.0. In the various forms of modified Newtonian theory, K is given values other than 2.0 depending on the type of modified Newtonian theory used. For this study, the coefficient suggested in Reference 5 was used. This coefficient is defined as:

$$K = \frac{\gamma + 3}{\gamma + 1}\left[1 - \frac{2}{\gamma + 3}\left(\frac{1}{M^2}\right)\right] . \tag{2}$$

For $\gamma = 1.4$ and $M = 10.15$, this parameter equals 1.83.

Prandtl-Meyer

This method assumes a simple, isentropic, characteristic expansion. The smooth contoured body is approximated by a series of small step-like expansions. The assumption that the flow conditions are constant along the emanated Mach lines leads to the conclusion that the velocity parallel to the Mach line must be constant. This leads to the following relationship between the body angle, θ, and the local Mach number:

$$-\theta = \sqrt{\frac{\gamma + 1}{\gamma - 1}} \tan^{-1} \sqrt{\frac{\gamma - 1}{\gamma + 1}\left(M_\ell^2 - 1\right)} - \tan^{-1} \sqrt{M_\ell^2 - 1} \, . \tag{3}$$

This equation is generally referred to as the Prandtl-Meyer function, and tabulated values of θ as a function of M_ℓ can be found in References 6 and 7.

Once the local Mach number is known, the surface pressure ratio may be calculated and, thus, the pressure coefficient:

$$C_p = \frac{2}{\gamma M^2}\left[\frac{P_\ell}{P_\infty} - 1\right] , \tag{4}$$

where

$$\frac{P_\ell}{P_\infty} = \frac{P_o}{P_\infty}\left[1 + \frac{\gamma - 1}{2} M_\ell^2\right]^{-\left(\frac{\gamma}{\gamma-1}\right)} . \tag{5}$$

Tangent Cone

This is an empirical method using oblique shock relations (Reference 8). A relationship between the body angle, shock angle, and Mach number is determined, from which the pressure coefficient may be determined:

$$C_p = 2 \sin^2 \theta \left[1 - \frac{(\gamma - 1)M_{ns}^2 + 2}{4(\gamma + 1)M_{ns}^2}\right]^{-1} , \tag{6}$$

where M_{ns} is the Mach number normal to the surface.

High Mach Number Base Pressure

This is a simple empirical relationship which states that the base pressure coefficient is inversely proportional to the square of the Mach number, i.e.,

$$C_p = -1.0M_\infty^{-2.0} \quad . \tag{7}$$

The above methods were used to predict the pressure over the various rectangular elements which were then integrated to determine the various aerodynamic coefficients.

Results and Discussion

Theoretical values of axial force coefficient, C_A, and pitching moment coefficient, C_m, are compared with experimental results in Figure 5 for the undamaged body. Excellent agreement between experimental and theoretical values for C_A were obtained throughout the angle-of-attack range. Theoretical values of C_m compare very well with experimental values at $\alpha = 0$ degrees, and above $\alpha = 10$ degrees, but are greater than the experimental values by approximately 25 percent at $\alpha = 5$ degrees.

Shown in Figures 6 and 7 are comparisons of theoretical and experimental values of C_A and C_m for the two damaged configurations. Theoretical and experimental axial force coefficients for both damaged configurations compare within 7 percent throughout the angle-of-attack range.

The pitching moment coefficient predicted by theory for the bent-nose configuration is the same as that obtained experimentally for $\alpha = 0$ degrees. However, the initial slope of the C_m curve obtained experimentally is greater than the theoretical value. Thus, the experimental trim angle (angle at which the moment is zero) for the bent-nose configuration is 4 degrees, and the theoretical prediction is 5 degrees.

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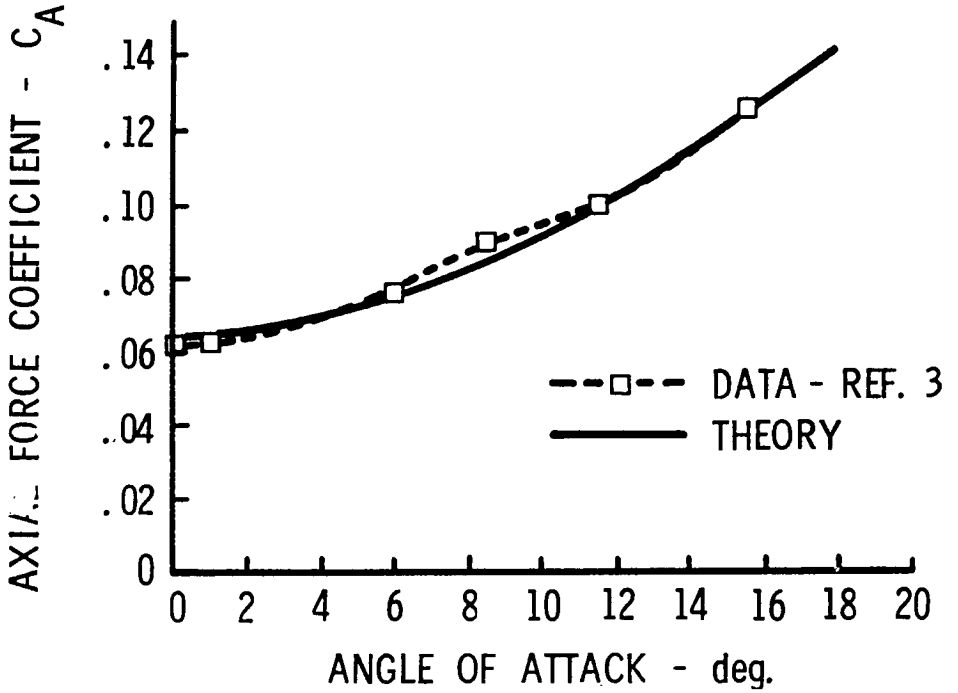

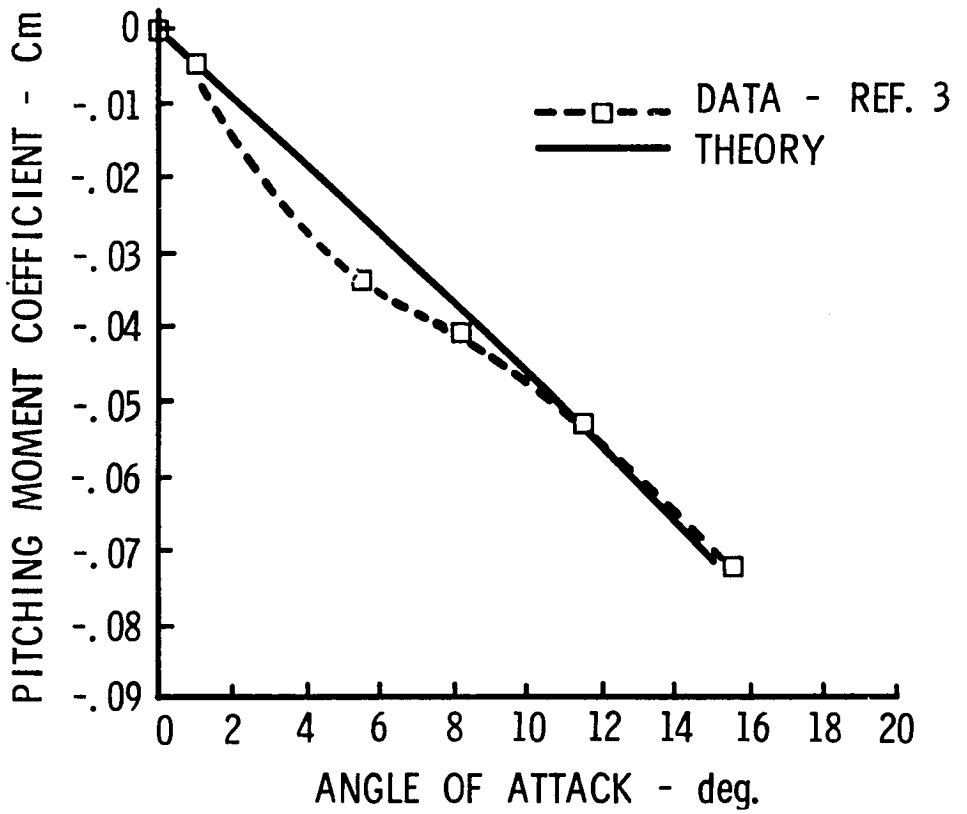

Figure 5. Axial Force and Pitching Moment Coefficients - Undamaged Configuration

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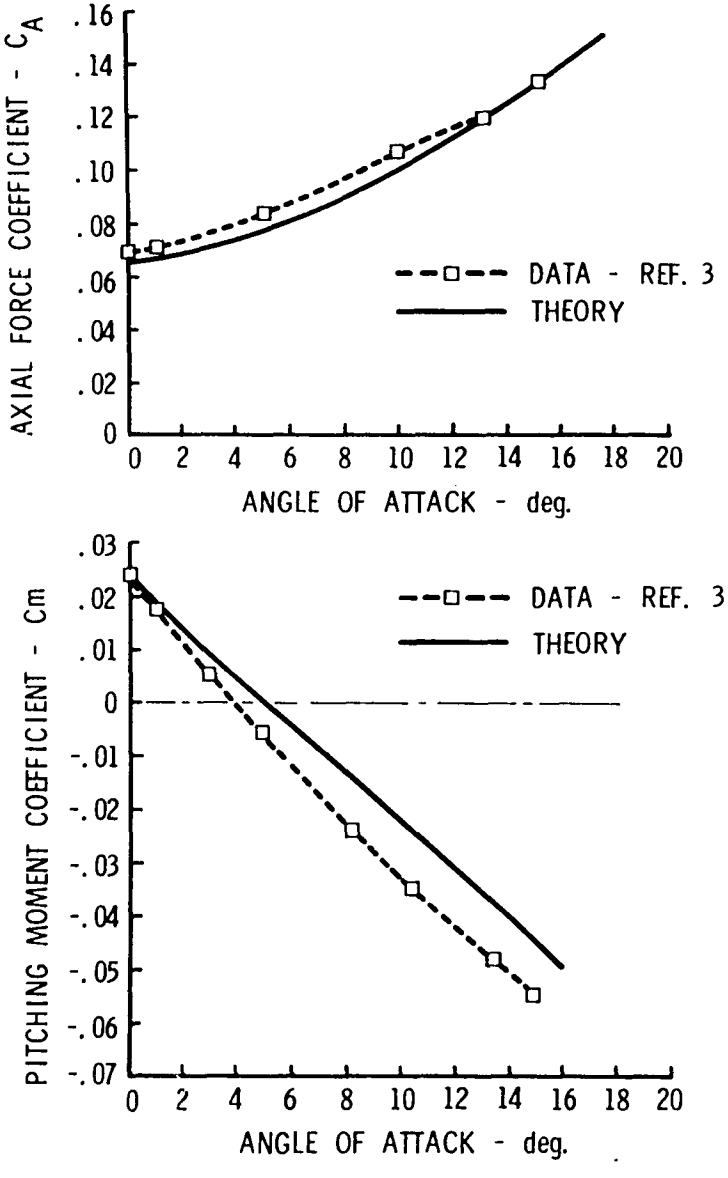

Figure 6. Axial Force and Pitching Moment Coefficients - Bent Nose Configuration

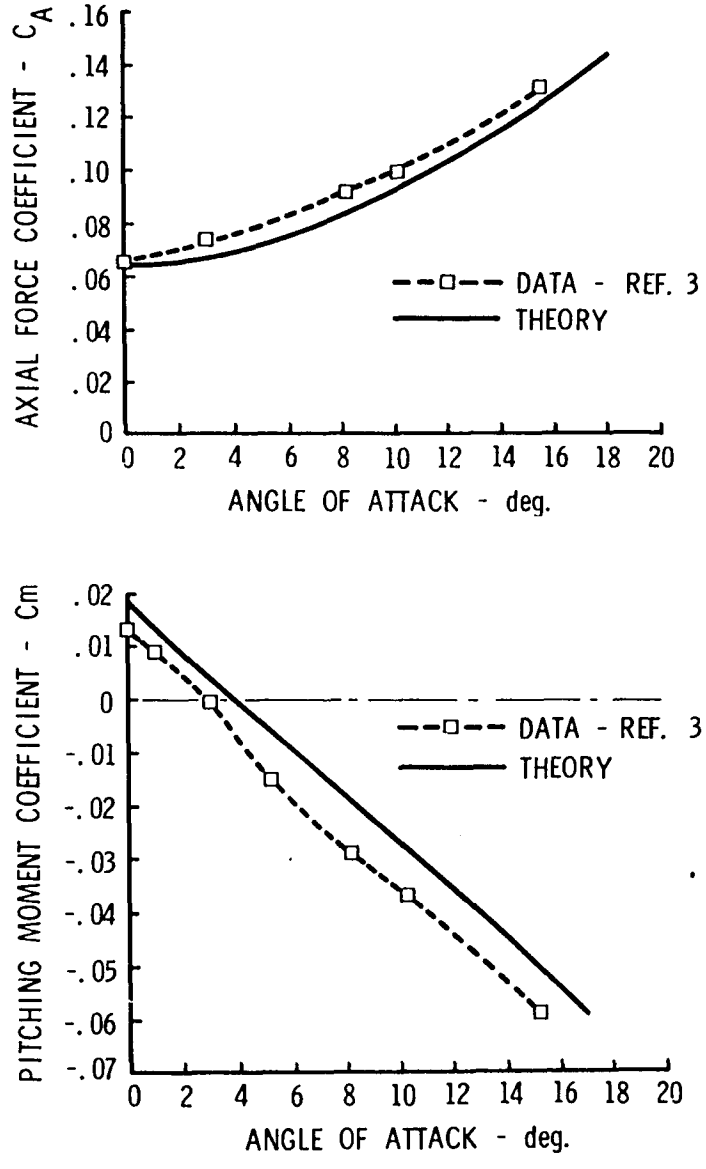

Figure 7. Axial Force and Pitching Moment Coefficients - Warped Configuration

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A quite different trend is noticed when comparing the experimental and theoretical values of C_m for the warped configuration. The slopes of the two C_m curves are almost the same, but the theoretical values are consistently higher than the experimental values by approximately 25 percent. Thus, the theoretical trim angle is 4 degrees and the experimental value is 3 degrees.

Therefore, for both damaged configurations, theory overpredicts the aerodynamic trim angle by 1 degree.

Conclusion

In light of the above discussion, it is felt that the analytical tools which are presently available are probably adequate for predicting the static aerodynamics of slightly deformed bodies for the purpose of flight dynamics analysis. This means that the theory is accurate enough to supplement, but not replace, experimental methods.

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