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COMPARISON OF HINGE MOMENTS FOR A SIMPLE DELTA WING AND A DELTA-WING ORBITER CONCEPT AT MACH 6

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With appendix by Frances T. Meissner

16. Abstract

Elevon hinge moments were determined from measured surface pressures on a typical delta-wing shuttle orbiter model at selective deflection angles for comparison with the extensive experimental and analytical hinge-moment data previously reported for a simple 75° delta wing with a trailing-edge control. The angles of attack were from 0° to 55° at elevon-deflection angles of -45.5°, 0°, and 20°. The results show that the elevon hinge moments on the shuttle orbiter are essentially the same as those measured earlier for the more basic model. Also included is an appendix describing a cubic spline function technique used to determine the hinge moments from elevon surface-pressure measurements.

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COMPARISONS OF HINGE MOMENTS FOR A SIMPLE DELTA WING
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SUMMARY

Elevon hinge moments were determined from measured surface pressures on a typical delta-wing shuttle orbiter model for comparison with the extensive experimental and analytical hinge-moment data of a simple 75° delta wing. Both investigations were conducted in the Langley 20-inch Mach 6 tunnel. For present tests the angles of attack were from 0° to 55° and the elevon-deflection angles were -45.5°, 0°, and 20°. The Reynolds numbers based on model length for the present and previous investigations were 5.32×10^6 and 4.03×10^6, respectively.

The investigation indicates that the hinge-moment data of the 75° delta wing are applicable to a representative concept of current delta-wing shuttle orbiters. The effects of the differences in leading-edge sweep, dihedral, and so forth, are washed out before reaching the elevons. Also, straightforward theoretical methods are applicable to the analysis and estimation of the elevon hinge moments.

INTRODUCTION

A class of delta-wing configurations, of which the space shuttle (ref. 1), and hypersonic transport (ref. 2) are examples, are presently being studied by NASA and industry. For such system designs, detailed analyses across the broad spectrum of engineering disciplines are required. In this respect, the maximum use of the large amounts of published data for various delta configurations should greatly reduce the amount of direct experimental support required for configuration definition.

An example of such published data is reference 3; this reference presents considerable experimental and analytical hinge-moment results for a 75° delta wing. The purpose of the present study was to examine the applicability of these results to a more complex delta-wing shuttle orbiter concept. Elevon hinge moments were determined from measured surface pressures on the orbiter and the data were compared with the results of the reference. Both investigations were conducted in the Langley 20-inch Mach 6 tunnel; the current tests are at angles of attack from 0° to 55° and elevon-deflection angles of -45.5°, 0°, and 20°.

SYMBOLS

A   aspect ratio; definite integral (see appendix)

b   span, cm

c   chord, cm

C_h elevon hinge-moment coefficient based on elevon dimensions (positive for trailing edge down, fig. 3(a)), $\dfrac{\text{Hinge moment}}{q_\infty S_e c_e}$

$C_{p,u}$ pressure coefficient for elevon upper surface

M_∞ free-stream Mach number

p   pressure, N/m^2

p/p_∞ ratio of static pressure on surface of elevon to free-stream static pressure

q_∞ free-stream dynamic pressure, N/m^2

S   surface area, cm^2

x   chordwise coordinate of elevon, cm

y   spanwise coordinate of elevon, cm

α angle of attack of delta-wing orbiter center line, deg

γ ratio of specific heats (1.4 for air)

δ_e elevon deflection angle (positive for trailing edge down), deg

Subscripts:

e   elevon

l lower

p	planform
u	upper
w	wing

APPARATUS AND TESTS

Tunnel

The Langley 20-inch Mach 6 tunnel is a blowdown type with air as the test medium. The general details of the tunnel operating characteristics along with schematic drawings and the Mach number calibration are presented in reference 4.

Models

A sketch and photograph of the delta-wing shuttle orbiter model used in the present study are presented in figure 1. Each elevon had twenty orifices; the left elevon had twenty on top and the right, twenty on the bottom. Figure 2 shows the size and average measured locations of the orifice on both elevons. The 75° simple delta-wing used in reference 3 is shown in figure 3. Mounting arrangement and orifice locations for the 75° delta wing are presented in reference 3.

Test Conditions

All the tests were conducted at an absolute stagnation pressure of approximately 18.7 atmospheres and a free-stream Reynolds number of 5.32×10^6 (based on model length). (1 atmosphere = 101.3 kN/m^2.) Tunnel stagnation temperature was maintained at about 478 K to avoid liquefaction of the air. The model angle of attack varied from 0° to 55° and the elevon deflection angles were -45.5^O, 0°, and 20°.

Methods

Small tubing (0.1016 cm outside diameter) was used from each orifice to the sting to minimize the bundle frontal area and to allow for better mobility when elevon deflection angles were changed. The bundle of tubes from each elevon was alined with the flow and was extended downstream to prevent interference with the flow over the other elevon. (See fig. 1(b).) Interference was only of concern on the lower surface since the body forms a barrier between the elevons on the top surface. Oil flows were conducted for each control deflection to insure that no interference occurred. At the sting the tubing size was jumped from 0.0762 to 0.1778 cm inside diameter to reduce lag time. The pressures were sensed by use of multiple-range electrical pressure transducers which are accurate to

approximately 1/4 percent of full scale on each range as shown in the following table:

p/p_∞	Error
0 to 1.1	±0.0028
1.1 to 3.3	±.0083
3.3 to 11	±.028
11 to 33	±.083
33 to 110	±.28

Angles of attack were set by use of a self-synchronous-motor counter system; the support system was rigid enough to insure that the deflection due to loads was less than $1/4^\circ$; therefore, no corrections to the angle of attack due to deflections were made.

The hinge moments were calculated from the measured pressure distributions by use of Control Data 6000 series computer and a curve-fitting, integration program described in the appendix. In this program cubic spline functions were curve fitted to the measured pressure differential between the upper and lower surfaces of the elevon along the parallel orifice rows shown in figure 2. Edge conditions were estimated by linear extrapolation by using the slope of the curves at the orifice nearest the edge. Spanwise and chordwise integration of the spline-function equations were used to obtain the hinge moments.

RESULTS AND DISCUSSION

Hinge Moments

Plots of the measured and calculated hinge moments for the 75° delta wing of reference 3 are reproduced in figure 4 and the measured hinge moments for the present delta-wing orbiter at $\delta_e = -45.5^\circ$, 0°, and 20° are superimposed on the plot. The two sets of data are in agreement at the points of comparison; thus, the values obtained on a sharp 75° delta wing are representative of the hinge moments on the type of configuration proposed for the shuttle. The configurational effects such as dihedral, sweep, and thickness are washed out before reaching the elevons. In addition, the applicability of commonly used theoretical methods to the analysis and estimation of the hinge moments is also established.

As shown in reference 3 and reaffirmed here, tangent-cone theory for the delta wing in conjunction with oblique-shock theory for the elevon can be used to determine the local flow properties over each. Figure 4 shows that the slopes of the hinge-moment curves

4

change at approximately the angles of attack for which these theories predict changes in flow regimes (supersonic to subsonic) on either the elevon or wing or on both. For supersonic flow on both the wing and elevon, the cited theories were used successfully to predict the hinge moments. When the flow becomes subsonic on either the elevon or both the wing and elevon, the assumption of a parabolic pressure distribution on the elevon predicts the hinge moment reasonably well. Further, the effect on the hinge moment of the wing-bow-shock intersection with the elevon shock (triple point) should be examined since if it occurs forward of the elevon trailing edge, the effect on the hinge moment can be strong and abrupt. (See fig. 4; $\delta_e = 20^O$.)

Elevon Pressure Distributions of Delta-Wing Orbiter

Since integrated forces and moments can conceal compensating variations in the pressure distributions, measured and calculated pressure distributions on the elevon at $\alpha = 30^O$ and $\alpha = 55^O$ are compared in figure 5. These two angles of attack were selected because at $\alpha = 30^O$ the flow over the elevon is supersonic whereas at $\alpha = 55^O$ it is subsonic. In general, the pressure distributions are relatively flat on both the upper and lower surfaces and the average levels on the lower surface are predicted reasonably well by the appropriate theories (tangent-cone oblique-shock and Prandtl-Meyer theory for supersonic flow and assumed parabolic pressure distributions for subsonic flow).

In reference 3 the hinge moments were obtained both by direct measurements by use of a strain-gage balance and by integration of pressure measurements on the lower surface by assuming the upper surface pressure to be given by $C_{p,u} = \dfrac{-1}{M_\infty^2}$. The agreement between the two sets of measured hinge moments was excellent. However, for the present tests where upper surface pressures were also measured, $C_{p,u} = \dfrac{-1}{M_\infty^2}$ was found to underpredict the pressure. This expression was derived empirically from experimental data up to $M_\infty \approx 2.2$ in reference 5 and extrapolated to higher Mach numbers. Because the pressure level on the upper surface is low in value and, in general, small relative to that of the lower surface, small errors in its prediction have little effect on the elevon normal force or hinge moment. However, for future reference a better representation of the average pressure on the elevon upper surface at Mach 6 was found to be given by $C_{p,u} = \dfrac{-2(\gamma-1/\gamma)}{M_\infty^2}$ as shown in figure 5.

CONCLUDING REMARKS

Elevon hinge moments were determined from measured surface pressures on a typical delta-wing shuttle orbiter model at selective deflection angles for comparison with the experimental and analytical hinge-moment data of a 75° delta wing with a trailing-edge

5

control. Both investigations were conducted in the Langley 20-inch Mach 6 tunnel. For the present tests the angles of attack were from 0° to 55° and the elevon deflection angles -45.5^O, 0°, and 20°. The Reynolds numbers based on model length for the present and previous investigations were 5.32×10^6 and 4.03×10^6, respectively.

The investigation shows that the hinge-moment data obtained on a simple, sharp 75° delta wing with a trailing-edge control are directly applicable to the more complex configuration of the present investigation. The effects of the marked differences in leading-edge sweep, dihedral thickness, and so forth, are washed out before reaching the elevons. Also, commonly used theoretical methods are applicable to the analysis and estimation of the elevon hinge moments.

Langley Research Center,
    National Aeronautics and Space Administration,
        Hampton, Va., December 22, 1971.

6

APPENDIX

A SPLINE FUNCTION TECHNIQUE FOR COMPUTING
ELEVON HINGE MOMENTS

By Frances T. Meissner
Langley Research Center

A cubic spline function technique is applied to pressure measurements obtained at orifices located in paired parallel rows on the top and bottom surfaces of an elevon to compute net force and elevon hinge moments. Linear extrapolation is applied to estimate edge variables. The advantage of cubic spline functions is that they are continuous and have continuous derivatives up to order two. This procedure, in most cases, leads to more accurate calculations of force and hinge moments than linear or quadratic approximations. The cubic spline technique is easy to apply and requires relatively little computer resources. Reference 6 gives a detailed explanation of the specific spline algorithms used in this application. Discussion herein is confined to the application of cubic spline functions to curve-fit pressure measurements, and ultimately, to yield force and hinge-moment computations.

The net force on a surface F and the hinge moment about the leading edge M_h can be expressed in the following manner:

$$\left.\begin{array}{l} F = \int_x \int_y \Delta p(x,y)\,dy\,dx \\[2em] M_h = \int_x \int_y x\,\Delta p(x,y)\,dx\,dy \end{array}\right\} \tag{A1}$$

where x and y are coordinate directions as shown in figure 2 and $\Delta p(x,y)$ is the difference in pressure above and below the elevon.
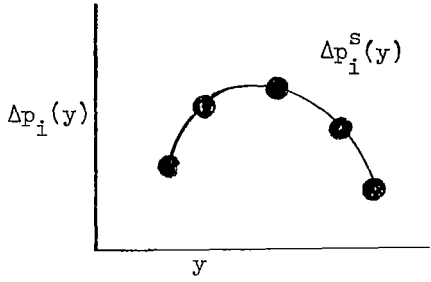
For a given row of paired orifices

$$\Delta p(x,y) = \Delta p_i(y)$$

where $i = 1 \ldots m$ refers to the ith row. For each pair of orifices, the subscript j is attached to y to indicate the location in a given row
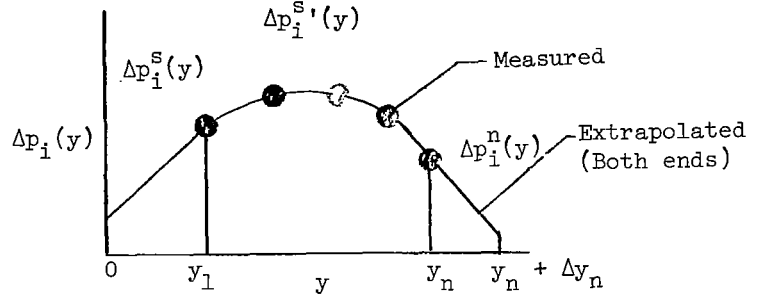
$$j = 1 \ldots n$$

Using the algorithm described in reference 7 a cubic spline function $\Delta p_i^S(y)$ is fitted through the differences $\Delta p_i(y_j)$ (sketch (a)) where s is a superscript signifying

Sketch (a)

Sketch (b)

spline. The spline function $\Delta p_i^S(y)$ consists of a set of cubic polynomial segments connected from point to point to form a continuous curve. At the junctions of the polynomial segments, the connected pair are constrained to have equal first and second derivatives as well as equal values.

Since there are no measurements at the edges of the elevon, pressure differences are extrapolated linearly in the y-direction to the edges. Linear extrapolation is performed by using the first derivative of the spline function $\Delta p_i^S(y)$ at $\Delta p_i^S(y_1)$ and $\Delta p_i^S(y_n)$. Using the cubic spline algorithm of reference 7 and linear extrapolation, the pressure difference approximation along a given row is (see sketch (b)):

$$\Delta \hat{p}_i(y) = \begin{cases} \dfrac{dp_i^S(y_1)}{dy}\left(y - y_1\right) + p_i^S\left(y_1\right) & \left(0 \leq y \leq y_1\right) \\ \Delta p_i^S(y) & \left(y_1 \leq y \leq y_n\right) \\ \dfrac{dp_i^S(y_n)}{dy}\left(y - y_n\right) + \Delta p_i^S\left(y_n\right) & \left(y_n \leq y \leq \left(y + \Delta y_n\right)\right) \end{cases} \quad \text{(A2)}$$

where $\Delta \hat{p}_i(y)$ are sets of simple polynomial functions. The definite integral is easily obtained by simple integration and evaluation at endpoints. The definite integrals are written as

$$A\left(x_i\right) = A_i = \int_y \Delta p_i(y) \, dy \quad \text{(A3)}$$

The force and hinge moment can now be written

$$
\left.
\begin{aligned}
F &= \int_X A(x)\,dx \\[2em]
M_h &= \int_X xA(x)\,dx
\end{aligned}
\right\}
\tag{A4}
$$

where $A(x)$ is not yet known in a functional form. Pressure is known at discrete points in the y-direction along a row; similarly $A(x)$ is known only at discrete distances in the x-direction. By using the algorithm of reference 7, a cubic spline function $A^S(x)$ is fitted through the $A(x_i)$ (sketch (b)) and $A^S(x)$ approximates $A(x)$ from the first to last row of orifices. The value of $A(x)$ is not known at the leading or trailing edge of the elevon and linear extrapolation is performed as before. The following representation is made for $A(x)$

$$
A(x) =
\begin{cases}
\dfrac{dA(x_1)}{dx}\left(x - x_1\right) + A\left(x_1\right) & \left(0 \le x \le x_1\right) \\[2em]
A^S(x) & \left(x_1 \le x \le x_m\right) \\[2em]
\dfrac{dA(x_m)}{dx}\left(x - x_m\right) + A\left(x_m\right) & \left(x_m \le x \le \left(x_m + \Delta x_m\right)\right)
\end{cases}
\tag{A5}
$$

where $A(x)$ is a set of single polynomials and the definite integral of $A(x)$ can be found as before by simple integration and evaluation. Thus, with an approximation $A(x)$, the force and hinge moments can be computed from the evaluation of the integrals of equations (A4).

A computer program which incorporates the algorithm of reference 7 with equations (A2) and (A5) along with their definite integrals has been written in FORTRAN IV for the Control Data 6000 series computer. The program is designed to operate in either a batch mode or from an on-line cathode ray tube (CRT) console. From the on-line console, plots of the pressure approximation functions, forces, and hinge moments are presented to the engineering analyst to verify and/or modify input based on engineering judgment.
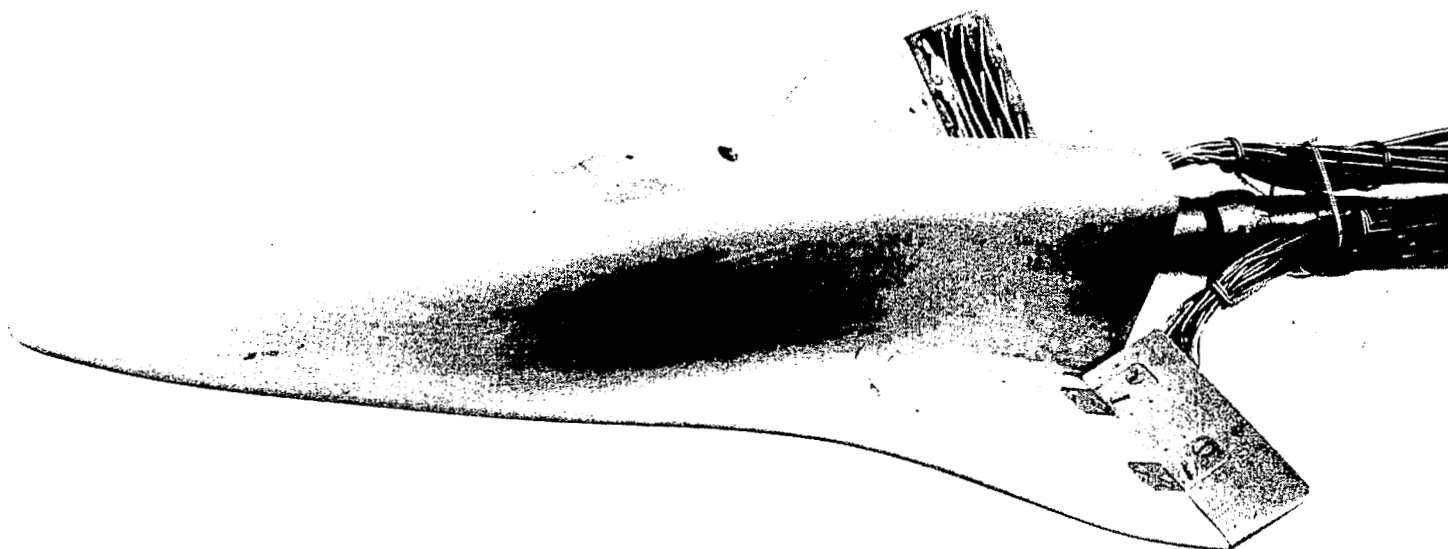
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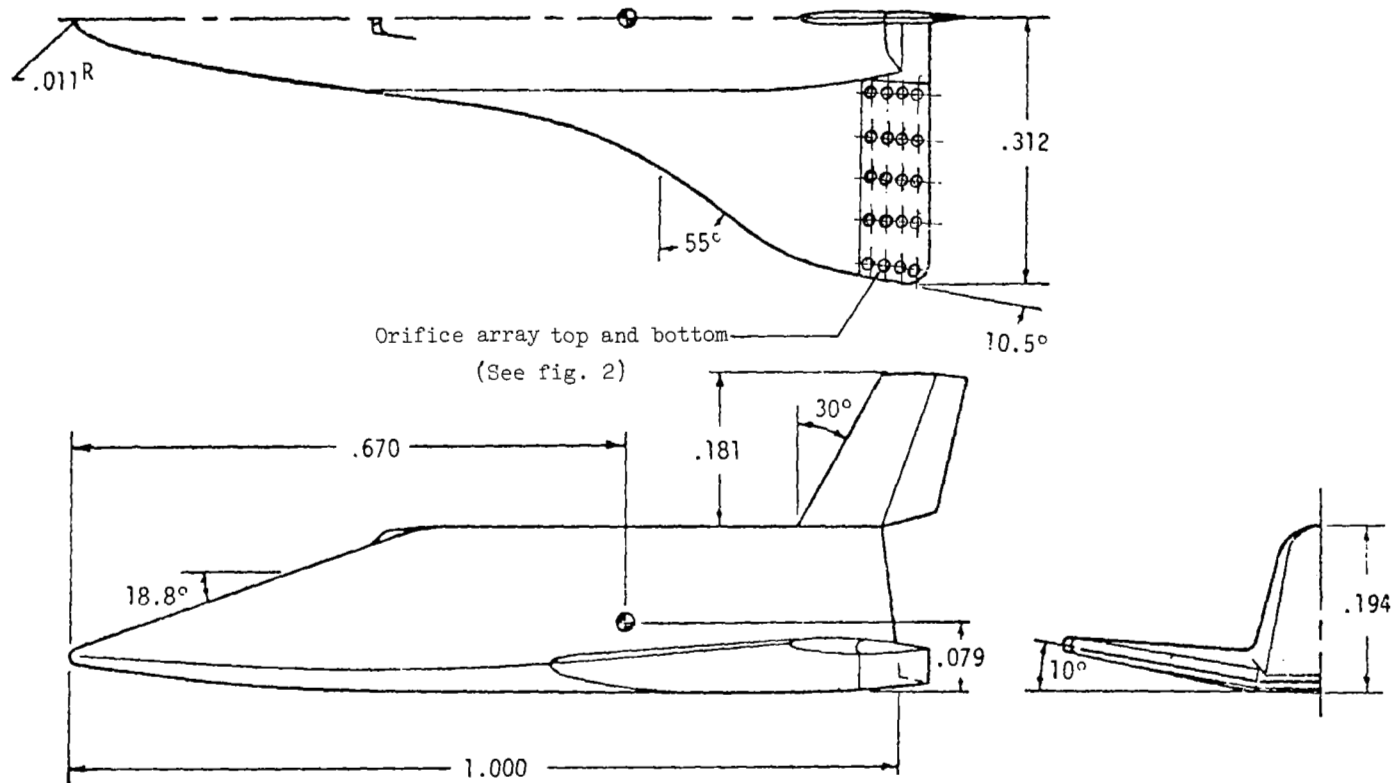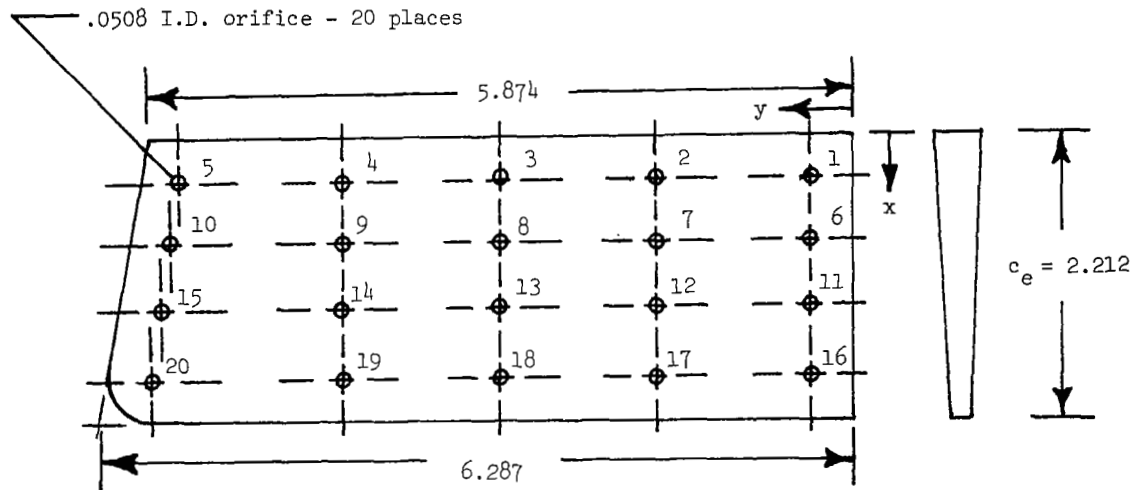
(a) General details.

Figure 1.- McDonnell Douglas baseline delta-wing orbiter (0050B). All linear dimensions are in terms of body length (26.5 cm). A_p = 1.894; S_p = 144.387 cm; b_p = 16.536 cm.

L-71-9017

(b) Model-tubing-sting arrangement.

Figure 1.- Concluded.

.0508 I.D. orifice - 20 places

5.874

y

5 4 3 2 1

10 9 8 7 6

x

15 14 13 12 11

$c_e = 2.212$

20 19 18 17 16

6.287

Orifice	x/c_e, %	y/b_e, %	Orifice	x/c_e, %	y/b_e, %
1	13.8	5.38	11	61.4	5.56
2		27.62	12		27.21
3		49.48	13		49.07
4		72.07	14		71.10
5		94.32	15		94.27
6	36.5	5.25	16	84.96	5.38
7		25.59	17		26.80
8		48.60	18		48.80
9		71.18	19		70.55
10		94.19	20		94.32

x/c_e, %	b_e
0	5.874
13.8	5.890
36.5	5.944
61.4	5.972
84.96	6.020
100.00	6.287

Figure 2.- Average locations of orifice on each elevon.

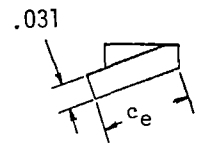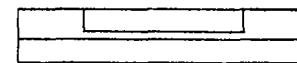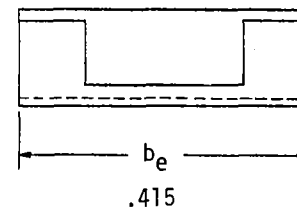All dimensions are in centimeters.
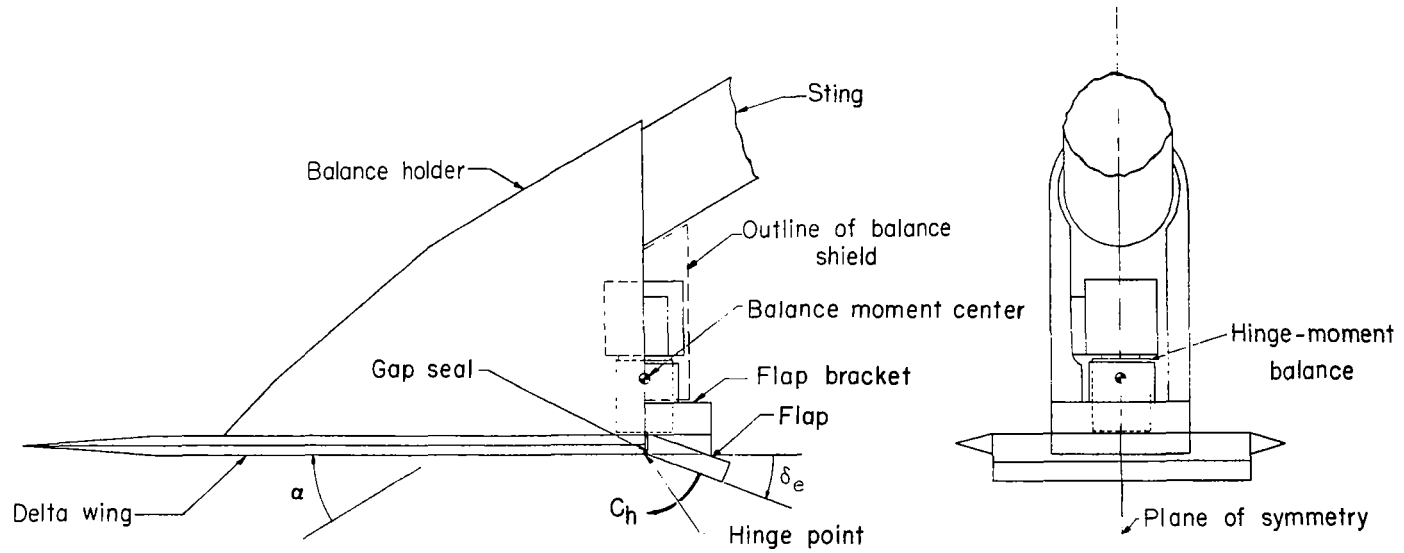
(a) Model assembly showing location of hinge-moment balance.

Figure 3.- Sketch of 75⁰ delta wing with trailing-edge control (ref. 3). All dimensions are in terms of wing center-line length (20.32 cm).

4.0°

1.0

.536

.415

75.0°

A

A

.635

30.0°
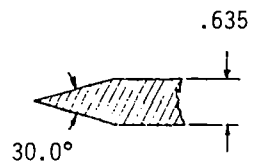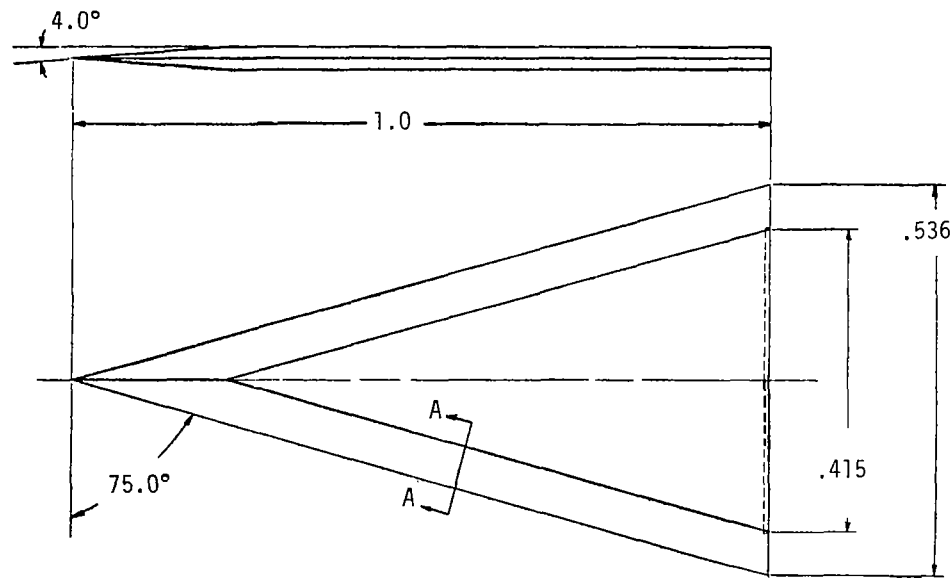
Section AA - leading edge

b_e

.415

.031

c_e

$\dfrac{S_e}{S_w}$	A_w	c_e
0.20	3.212	.129

Elevon

(b) Wing details.
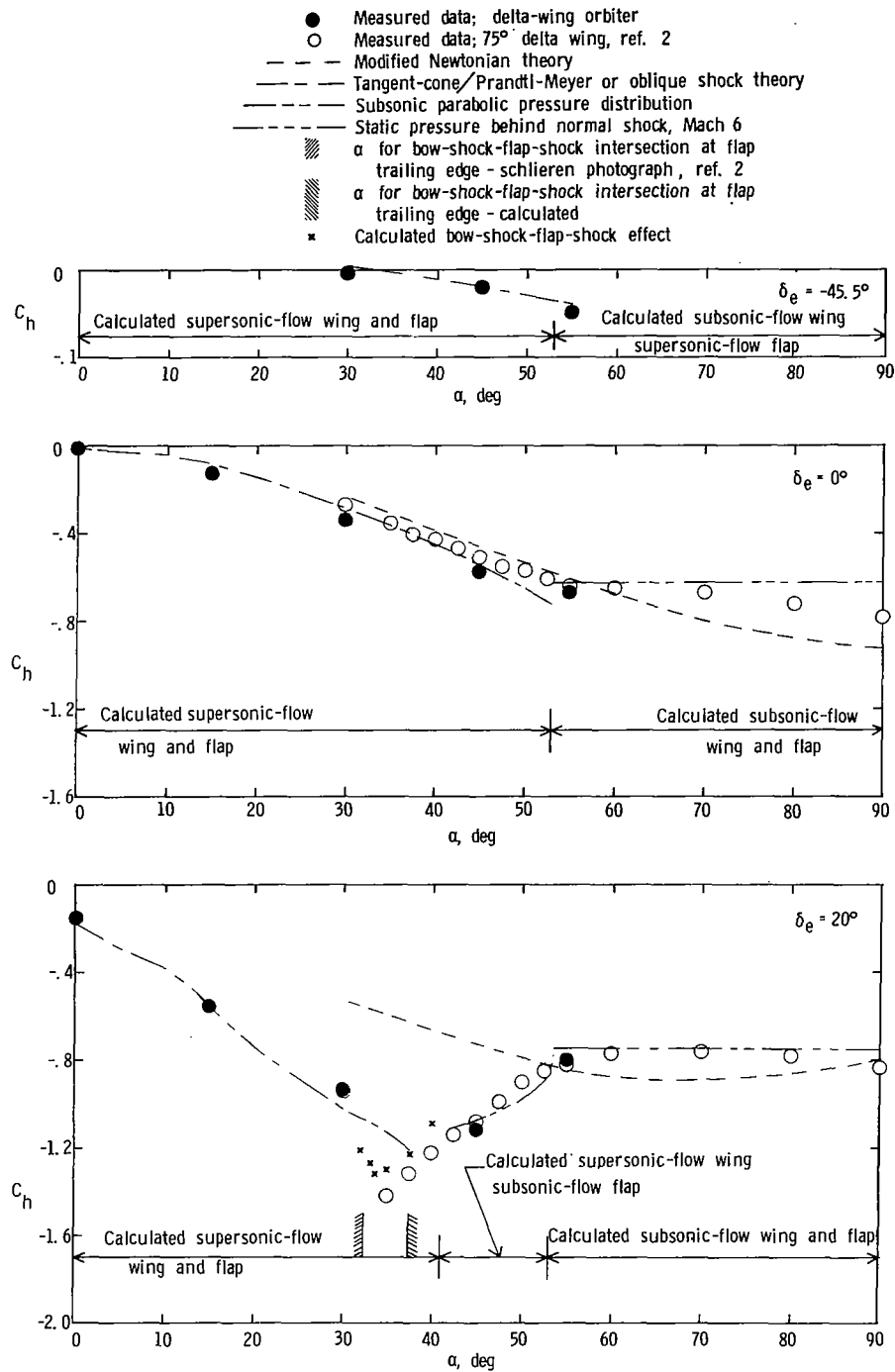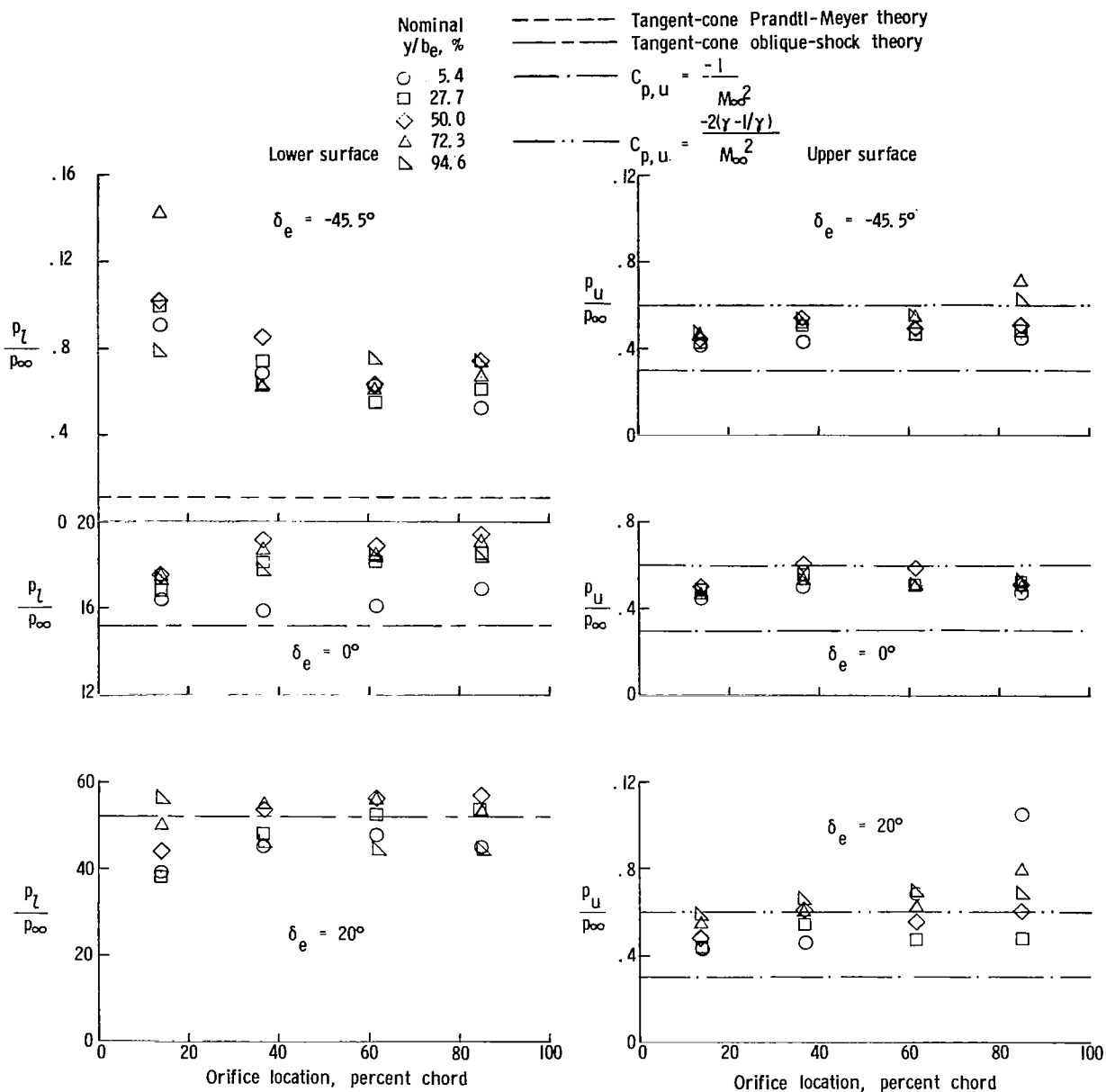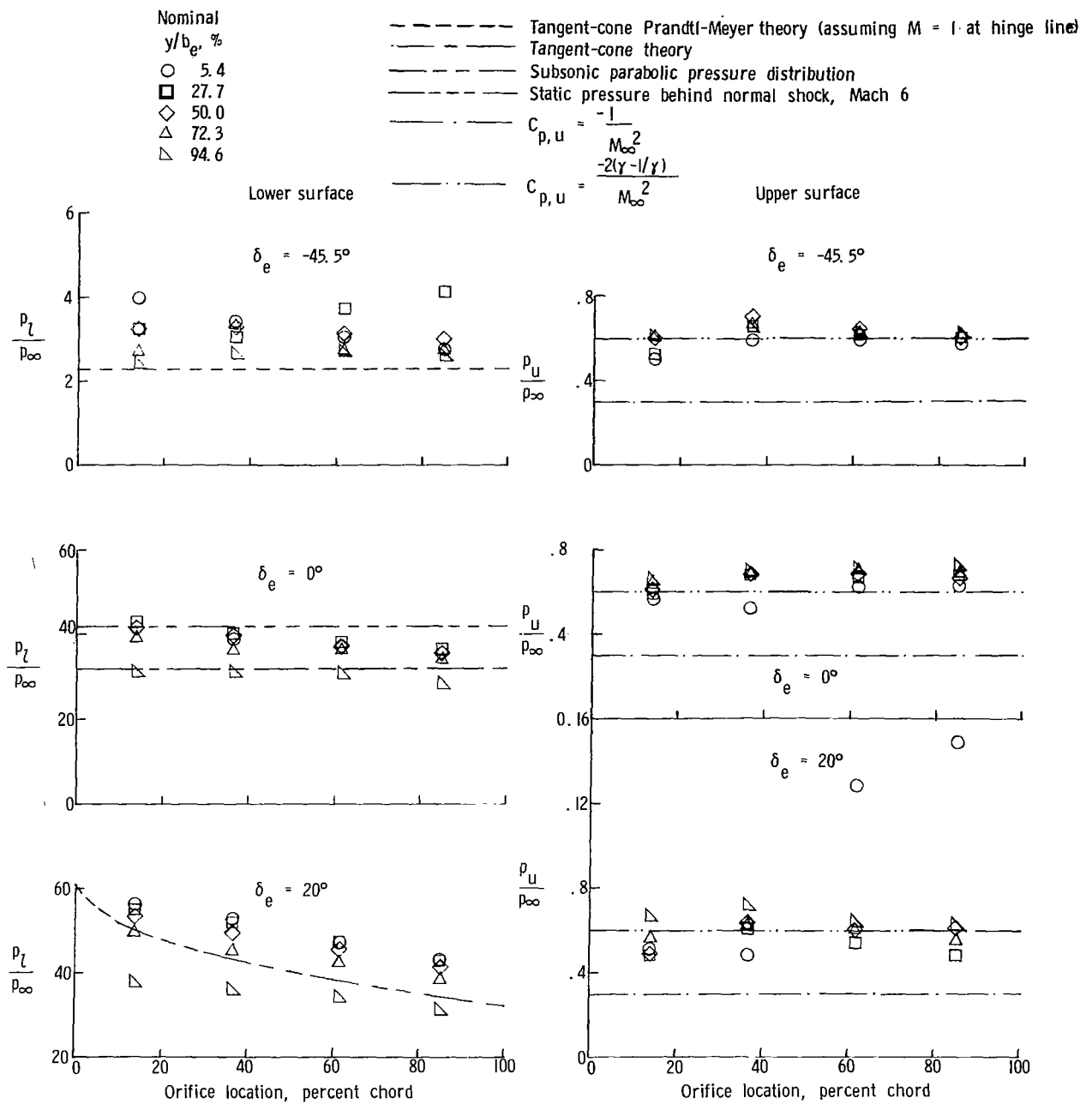
Figure 3.- Concluded.

Figure 4.- Comparison of hinge-moment coefficients for a delta-wing shuttle orbiter with those of a 75° delta wing and theory.

(a) $\alpha = 30^{\circ}$.

Figure 5.- Pressure distributions on upper and lower elevon surface of present configuration and comparison with theory. Note the scale changes.

Nominal
y/b_e, %

○ 5.4
□ 27.7
◇ 50.0
△ 72.3
◺ 94.6

— — — — Tangent-cone Prandtl-Meyer theory (assuming M = 1 at hinge line)
— — — Tangent-cone theory
— — Subsonic parabolic pressure distribution
——— Static pressure behind normal shock, Mach 6

$$C_{p,u} = \frac{-1}{M_\infty^2}$$

$$C_{p,u} = \frac{-2(\gamma-1/\gamma)}{M_\infty^2}$$

Lower surface

Upper surface

$\delta_e = -45.5°$

$\delta_e = -45.5°$

$\frac{p_\ell}{p_\infty}$

$\frac{p_u}{p_\infty}$

$\delta_e = 0°$

$\frac{p_\ell}{p_\infty}$

$\frac{p_u}{p_\infty}$

$\delta_e = 0°$

$\delta_e = 20°$

$\delta_e = 20°$

$\frac{p_\ell}{p_\infty}$

$\frac{p_u}{p_\infty}$

$\delta_e = 20°$

Orifice location, percent chord

Orifice location, percent chord

(b) $\alpha = 55°$.

Figure 5.- Concluded.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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