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NASA TECHNICAL NOTE

NASA TN D-7470

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EXTRACTION FROM FLIGHT DATA OF LONGITUDINAL AERODYNAMIC COEFFICIENTS FOR F-8 AIRCRAFT WITH SUPERCRITICAL WING

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1974

1. Report No. NASA TN D-7470	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EXTRACTION FROM FLIGHT DATA OF LONGITUDINAL AERODYNAMIC COEFFICIENTS FOR F-8 AIRCRAFT WITH SUPERCRITICAL WING		5. Report Date May 1974
		6. Performing Organization Code
7. Author(s) James L. Williams and William T. Suit		8. Performing Organization Report No. L-9203
		10. Work Unit No. 501-26-05-02
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Va. 23665		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Note
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The longitudinal aerodynamic derivatives of the F-8 aircraft with supercritical wing were obtained from flight data by a parameter-extraction algorithm at Mach numbers of 0.8, 0.9, and 0.98. A set of derivatives were obtained from which calculated aircraft responses were correlated almost identically with actual flight responses. In general, the trends of the extracted derivatives obtained by the algorithm agreed with those obtained by a Newton-Raphson method and with preliminary data from the Langley 8-foot transonic pressure tunnel.

The wind-tunnel damping derivatives were, however, substantially higher than the converged damping derivatives possibly because of Reynolds number differences between flight and model tests.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Parameter extraction Longitudinal aerodynamic coefficients Maximum likelihood	Unclassified – Unlimited STAR Category 02

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	25	3.25

*For sale by the National Technical Information Service, Springfield, Virginia 22151

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SUMMARY

A parameter-extraction algorithm was used to determine the longitudinal aerodynamic derivatives from flight data for the F-8 aircraft with supercritical wing. The flight data were the responses to horizontal-tail pulses and the data used were for Mach numbers of 0.80, 0.90, and 0.98.

Results of this study showed that a set of derivatives were determined which yielded a calculated aircraft response almost identical with the measured response in flight.

In addition, results of this study showed that the trends of the converged derivatives with Mach numbers were generally similar to the trends obtained by using a Newton-Raphson method. At the highest Mach number, the converged damping derivative was substantially lower than the value of the damping derivative obtained from preliminary tests in the Langley 8-foot transonic pressure tunnel. This lack of agreement probably resulted from the difference in Reynolds number between the flight and wind-tunnel tests.

INTRODUCTION

Analytical and simulator studies of the flight and handling qualities of aircraft require that accurate estimates of the aerodynamic parameters be used if the results are to be valid. To provide aerodynamic parameters for analytical and simulator studies and to also provide numerical values for comparison with wind-tunnel data and theoretical estimates, parameters have been extracted from flight data for many years. Results from recent studies made at the Langley Research Center relating to parameter extraction for several aircraft are reported in references 1 to 4.

Various techniques for parameter extraction are presented in reference 5. The technique and program used in extracting the parameters in this study are those of the maximum likelihood method of reference 6.

The purpose of the present study is to extract longitudinal aerodynamic parameters from flight tests of the F-8 supercritical-wing aircraft at Mach numbers of 0.80, 0.90, and 0.98.

SYMBOLS

A_X, A_Z linear accelerations, g units

C_m pitching-moment coefficient about Y body axis

$C_{m_q} = \frac{\partial C_m}{\partial \left(\frac{q\bar{c}}{2V}\right)}$

$C_{m_\alpha} = \frac{\partial C_m}{\partial \alpha}$, per radian

$C_{m_{\dot{\alpha}}} = \frac{\partial C_m}{\partial \left(\frac{\dot{\alpha}\bar{c}}{2V}\right)}$

$C_{m_{\delta_h}} = \frac{\partial C_m}{\partial \delta_h}$, per radian

C_X force coefficient along X body axis

$C_{X_\alpha} = \frac{\partial C_X}{\partial \alpha}$, per radian

C_Z force coefficient along Z body axis

$C_{Z_\alpha} = \frac{\partial C_Z}{\partial \alpha}$, per radian

$C_{Z_{\delta_h}} = \frac{\partial C_Z}{\partial \delta_h}$, per radian

$\bar{c}$ mean geometric chord, m

$DE = \delta_h - \delta_{h,t}$, rad

g gravitational acceleration, $1g = 9.81 \text{ m/sec}^2$

h_p pressure altitude, m

I_X, I_Y, I_Z	moment of inertia about the roll, pitch, and yaw axis, kg-m^2
I_{XZ}	product of inertia, kg-m^2
l_h	distance from aircraft center of gravity to quarter-chord point of mean aerodynamic chord of horizontal tail, m
N	number of data points
p	roll rate, rad/sec
q	pitch rate, rad/sec
$R_q = \frac{1}{W_q}$	
$R_u = \frac{1}{W_u}$	
$R_w = \frac{1}{W_w}$	
r	yaw rate, rad/sec
S	wing area, m^2
u	velocity component along X body axis, m/sec
V	resultant velocity, m/sec
v	velocity component along Y body axis, m/sec
W	aircraft weight, N
W_q, W_u, W_w	weighting value of q, u, and w state variables
w	velocity component along Z body axis, m/sec
X	vector of aircraft states

α	angle of attack, deg or rad
β	angle of sideslip, deg or rad
δ_h	horizontal-tail deflection (positive for trailing edge down), deg or rad
θ	pitch attitude angle, deg or rad
ρ	mass density of air, kg/m^3
ϕ	roll attitude, rad

Subscripts:

c	computed
h	horizontal tail
m	measured in flight
t	indicates state at trim conditions

The dot over a symbol denotes rate of change with respect to time.

EQUATIONS OF MOTION

The equations of motion used in this study are referred to a body-axis system (fig. 1) and are as follows:

X Translational direction:

$$\dot{u} = rv - qw - g \sin\theta + \frac{1}{2}\rho V^2 S \frac{g}{W}\left[C_{X,t} + C_{X_\alpha}\left(\alpha - \alpha_t\right)\right]$$

Z Translational direction:

$$\dot{w} = qu - pv + g \cos\theta \cos\phi + \frac{1}{2}\rho V^2 S \frac{g}{W}\left[C_{Z,t} + C_{Z_\alpha}\left(\alpha - \alpha_t\right) + C_{Z_{\delta_h}}\left(\delta_h - \delta_{h,t}\right)\right]$$

Pitching moment:

$$\dot{q} = \frac{I_Z - I_X}{I_Y} pr + \frac{I_{XZ}}{I_Y}\left(r^2 - p^2\right) + \frac{1}{2}\frac{\rho V^2 S\bar{c}}{I_Y}\left[C_{m,t} + C_{m_\alpha}\left(\alpha - \alpha_t\right) + C_{m_q}\frac{q\bar{c}}{2V}\right.$$

$$\left. + C_{m_{\dot{\alpha}}}\frac{\dot{\alpha}\bar{c}}{2V} + C_{m_{\delta_h}}\left(\delta_h - \delta_{h,t}\right)\right]$$

The lateral variables v, p, and r were found to be small, and hence the nonlinear terms in these equations were negligible for these calculations.

DESCRIPTION OF AIRPLANE

The airplane for which the aerodynamic parameters were extracted is the F-8 airplane on which the original wing was replaced with a supercritical wing. The aircraft is a single-seat high performance airplane with a single jet engine embedded in the fuselage and a unit horizontal tail. Figure 2 is a photograph of the airplane. Pertinent geometric characteristics of the airplane are given in table I.

Flight instrumentation appropriate to this study included the following items:

(1) Pitch-rate gyro

(2) Angle-of-attack indicator

(3) Altimeter

(4) Total velocity indicator

(5) Horizontal-tail position indicator

(6) Magnetic tape recorders

(7) Accelerometers

The full-scale range of the flight instruments and their accuracies are given in table II.

FLIGHT TESTS

The data which are used in the present investigation were obtained from in-flight measurement of the airplane response to a horizontal-tail input. These flights were made at the NASA Flight Research Center as part of a general evaluation program of the F-8 supercritical-wing aerodynamics. Data were obtained at Mach numbers of about 0.80, 0.90, and 0.98. The control input used to generate the longitudinal motion were one or more horizontal-tail pulses. All data used in the study were reduced at Flight Research Center and have been corrected for bias and displacement of the measuring instrument from the aircraft center of gravity. A list of the test conditions and mass characteristics are presented in table III.

DERIVATIVE-EXTRACTION PROCEDURE

The parameter-extraction procedure used in this study is an iterative technique which utilizes the maximum likelihood method to estimate the stability and control parameters. This method uses the likelihood function which, when maximized, provides the following information:

(1) The parameter changes which are used to update the parameter

(2) The covariance matrices whose elements are proportional to the estimated standard deviations and the pairwise correlation coefficients for the parameters and the states

(3) The performance index function J which is an indicator of the fit between measured and calculated motions

Details of the method are given in reference 6.

The iterative technique produces a set of estimated derivatives which, when used in the equations of motion, provide the best fit to the time variation of the aircraft motion measured in flight. The criterion for the best fit is the performance index J which is defined as:

$$J = \det\left[\frac{1}{N}\sum_{i=1}^{N}\left(X_{i,m} - X_{i,c}\right)\left(X_{i,m} - X_{i,c}\right)^{T}\right]$$

where det means determinant, T means transpose, and X is the vector describing the state of the aircraft. Generally, the performance index J becomes smaller with successive iterations. The iteration procedure is stopped when the value of J does not change appreciably for several successive iterations. The components of the vector X are the state variables u, w, q, θ, and A_Z. The linear acceleration A_X was not included in the X vector since this variable was generally small. The quantities u_m and w_m were not measured directly but were obtained from the measured total velocity and angle of attack through the use of equations:

$$u_m = V_m \cos \alpha_m$$

$$w_m = V_m \sin \alpha_m$$

Maximization of the likelihood function yields the covariance matrix for the measurement noise based on the current nominal solution. (See ref. 6.) This matrix gives the variances (or standard deviations) of the differences of the measured state and the nominal solution. The inverse of this matrix is the weighting matrix used in the parameter-change equations. In this investigation, the diagonal form of the weighting matrix was used and the diagonal elements can be expressed as the squares of the difference between the measured and calculated data. For example, the weight for the state variable u is expressed as

$$\frac{1}{R_u^2} = \frac{1}{N} \sum_{i=1}^{N} \left(u_m - u_c\right)_i^2$$

Similar equations are obtained for $1/R_w^2$ and $1/R_q^2$.

Initial values of the state variable were obtained from the flight records for the time period just prior to a control input. Initial values of the aerodynamic derivatives were obtained from a preliminary investigation in the Langley 8-foot transonic pressure tunnel and these values are listed in table IV. Although the tabulated derivatives were for a Mach number of 0.8, they were used as initial values for all the work presented herein.

RESULTS AND DISCUSSION

The aerodynamic derivatives of table IV were used as starting values in the parameter-estimation process for each flight condition. Preliminary results indicated a high correlation between $C_{Z_{\delta_h}}$ and $C_{m_{\delta_h}}$, and also between C_{m_q} and $C_{m_{\dot{\alpha}}}$. These correlations had been observed in several other parameter-extraction studies and, therefore, were expected. The correlation problem was circumvented by fixing $C_{m_{\dot{\alpha}}}$ at -7.00 (the estimated value from table IV) and letting the computer search for C_{m_q}. The correlation between $C_{m_{\delta_h}}$ and $C_{Z_{\delta_h}}$ was circumvented by using the geometric relationship

$$C_{Z_{\delta_h}} = \frac{\bar{c}}{l_h} C_{m_{\delta_h}}$$

and searching for $C_{m_{\delta_h}}$.

The preliminary results also showed that the derivative C_{X_α} had a very large variance, which meant that it was not well defined. It was also found that C_{X_α} could be varied over a rather large range of values without appreciably affecting the computed time histories or the other extracted derivatives. The inaccuracy in this derivative resulted from the fact that only small changes in the forward velocity u of the aircraft occurred after the control input (A_X small) and this derivative occurs in the equation for forward velocity. The strategy employed in selecting a value for C_{X_α} was to try a range of values, and to select that value which resulted in the smallest variances in the states at convergence. The value selected was $C_{X_\alpha} = 0.58$. It appeared to be of reasonable magnitude, and was therefore held constant during the iterative process for each flight condition.

Calculated time histories obtained after convergence, and with the constraints noted, are shown in figures 3, 4, and 5 for Mach numbers of 0.80, 0.90, and 0.98, respectively. The calculated time histories are almost identical with the flight records.

The extracted derivatives and their estimated standard deviations are listed in table V. The extracted derivatives appear to be well defined. There are no standard deviations listed for C_{X_α}, C_{Z_δ}, and $C_{m_{\dot{\alpha}}}$ since these were constrained to the tabulated values, as mentioned previously.

The more important extracted derivatives of table V are presented in figure 6 as functions of Mach number. Also shown are values from preliminary tests in the Langley 8-foot transonic pressure tunnel and extracted derivatives from flight tests calculated by using a Newton-Raphson method (ref. 7). In general, the extracted derivatives (the present study and the Newton-Raphson method (ref. 7)) are in good agreement with the wind-tunnel values. However, the extracted effective damping-in-pitch parameter $-\left(C_{m_q} + C_{m_{\dot{\alpha}}}\right)$ has a trend with Mach number which is opposite (lower value) that obtained from wind-tunnel tests in the Mach number range from 0.90 to 1.00. One reason for this difference can be attributed to a Reynolds number effect; since, in general, the Reynolds number for the present tests was about 10 times the Reynolds number of the wind-tunnel tests at these Mach numbers.

CONCLUDING REMARKS

A parameter-extraction algorithm was used to determine the longitudinal aerodynamic derivatives from flight data for the F-8 aircraft with supercritical wing. The flight data were the responses to horizontal-tail pulses and the data used were for Mach numbers of 0.80, 0.90, and 0.98.

Results of this study showed that a set of derivatives were determined which yielded a calculated aircraft response almost identical with the measured response in flight.

In addition, results of this study showed that the trends of the converged derivatives with Mach number were generally similar to the trends obtained with the Newton-Raphson method. At the highest Mach number, the converged damping derivative was substantially lower than the value of the damping derivative obtained from preliminary tests in the Langley 8-foot transonic pressure tunnel. This discrepancy appears to be caused by a difference in Reynolds numbers between the flight and wind-tunnel tests.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., January 10, 1974.

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TABLE I.- GEOMETRIC CHARACTERISTICS OF F-8 AIRCRAFT

Fuselage:	
Length, m	16.09
Wing:	
Area, m^2	25.50
Aspect ratio	6.77
Span, m	13.14
Mean geometric chord, m	2.08
Vertical tail:	
Area, m^2	10.13
Aspect ratio	1.5
Span, m	3.89
Rudder:	
Area, m^2	1.17
Horizontal tail:	
Area, m^2	8.68
Aspect ratio	3.5
Span, m	5.52
Tail length, center of gravity to quarter-chord point of mean geometric chord, m	5.31

TABLE II.- INSTRUMENT RANGES AND ACCURACIES

Instrument	Range	Accuracy
Pitch rate	±40 deg/sec	±0.8 deg/sec
Angle of attack	-5° to $+25^{\circ}$	$\pm 0.3^{\circ}$
Pressure altitude	0 to 18 000 m	±0.024 kN/m^2
Total velocity	0 to 360 m/sec	±0.7 m/sec
Horizontal-tail position	-25° to 7°	$\pm 0.4^{\circ}$
Normal acceleration at c.g.	-1g to +4g	±0.06g
Longitudinal acceleration at c.g.	±0.5g	±0.01g
Pitch angle	$\pm 30^{\circ}$	$\pm 0.6^{\circ}$

TABLE III.- TEST CONDITIONS AND MASS CHARACTERISTICS

Weight, N	Mass, kg	I_X, $kg\text{-}m^2$	I_Y, $kg\text{-}m^2$	I_Z, $kg\text{-}m^2$	I_{XZ}, $kg\text{-}m^2$	h_p, m	l_h, m
Mach number, 0.80							
105 981	10 807.0	20 519.9	125 574.1	139 580.1	4559.5	11 264.0	5.31
Mach number, 0.90							
104 722	10 678.7	20 511.2	125 305.9	139 319.8	4514.6	11 274.2	5.30
Mach number, 0.98							
101 982	10 399.3	20 492.3	124 660.9	138 693.6	4406.5	13 856.0	5.27

TABLE IV.- STARTING VALUES OF AERODYNAMIC DERIVATIVES

C_{X_α}	C_{Z_α}	$C_{Z_{\delta_h}}$	C_{m_α}	$C_{m_{\dot{\alpha}}}$	C_{m_q}	$C_{m_{\delta_h}}$
-0.29	-6.13	-0.91	-1.14	-7.0	-41.6	-2.69

TABLE V.- EXTRACTED AERODYNAMIC PARAMETERS AND STANDARD DEVIATION

Coefficients	Parameters and standard deviations[a] at Mach number of –					
	0.81		0.90		0.98	
$C_{X,t}$	0.03	(0.00)	0.02	(0.00)	0.02	(0.00)
C_{X_α}	[b]0.58		[b]0.58		[b]0.58	
$C_{Z,t}$	-0.44	(0.00)	-0.44	(0.00)	-0.44	(0.00)
C_{Z_α}	-6.02	(0.08)	-6.95	(0.13)	-7.49	(0.24)
$C_{Z_{\delta_h}}$	[b]-0.92		[b]-1.01		[b]-0.97	
$C_{m,t}$	0.003	(0.00)	0.003	(0.03)	0.00	(0.00)
C_{m_α}	-1.62	(0.01)	-2.04	(0.10)	-3.31	(0.02)
$C_{m_{\dot{\alpha}}}$	[b]-7.00		[b]-7.00		[b]-7.00	
C_{m_q}	-27.82	(1.04)	-29.17	(1.83)	-16.59	(2.60)
$C_{m_{\delta_h}}$	-2.34	(0.02)	-2.58	(0.73)	-2.46	(0.07)

[a]Standard deviations are given in parentheses.

[b]Used as constants.

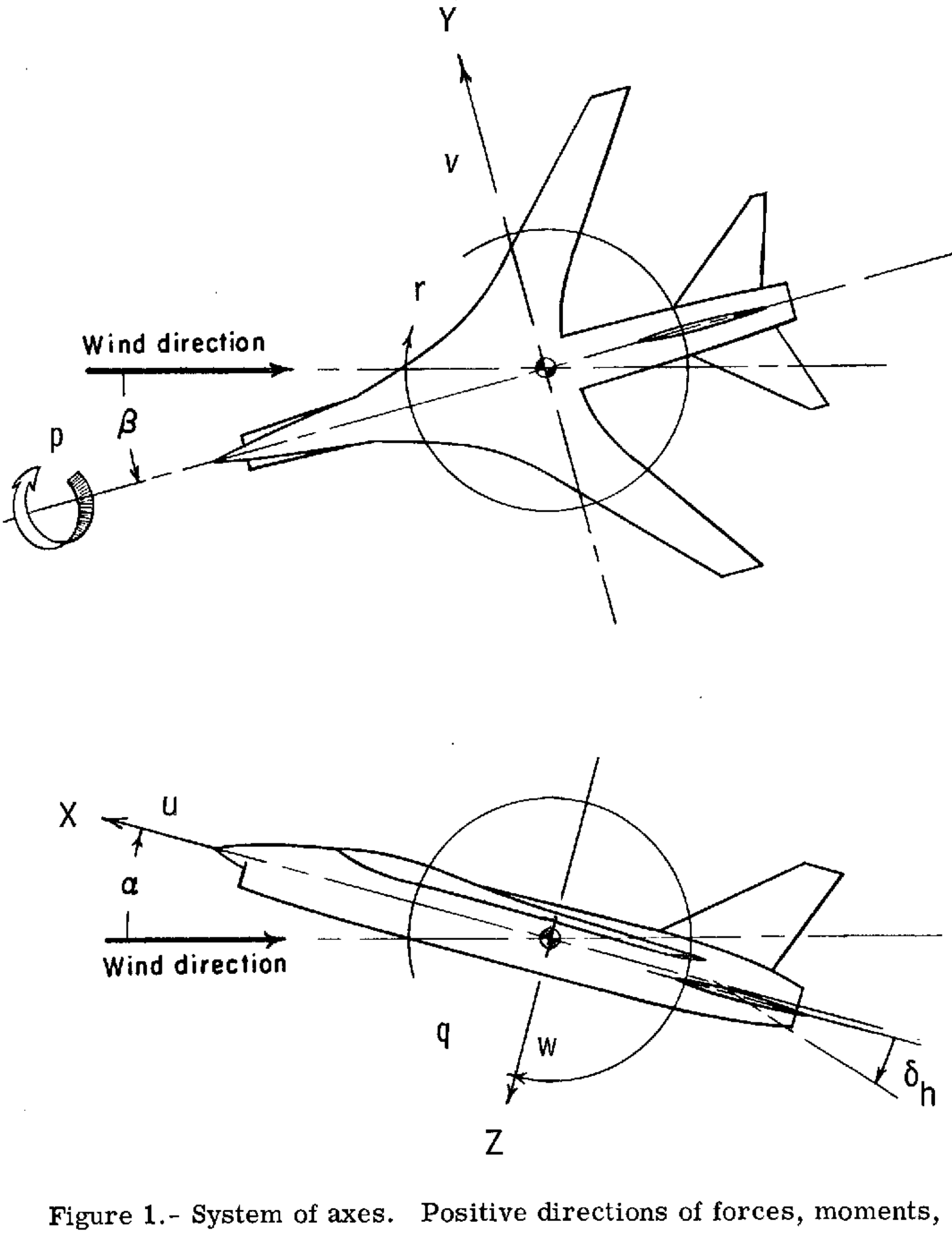

Figure 1.- System of axes. Positive directions of forces, moments, and angles are indicated by arrows.

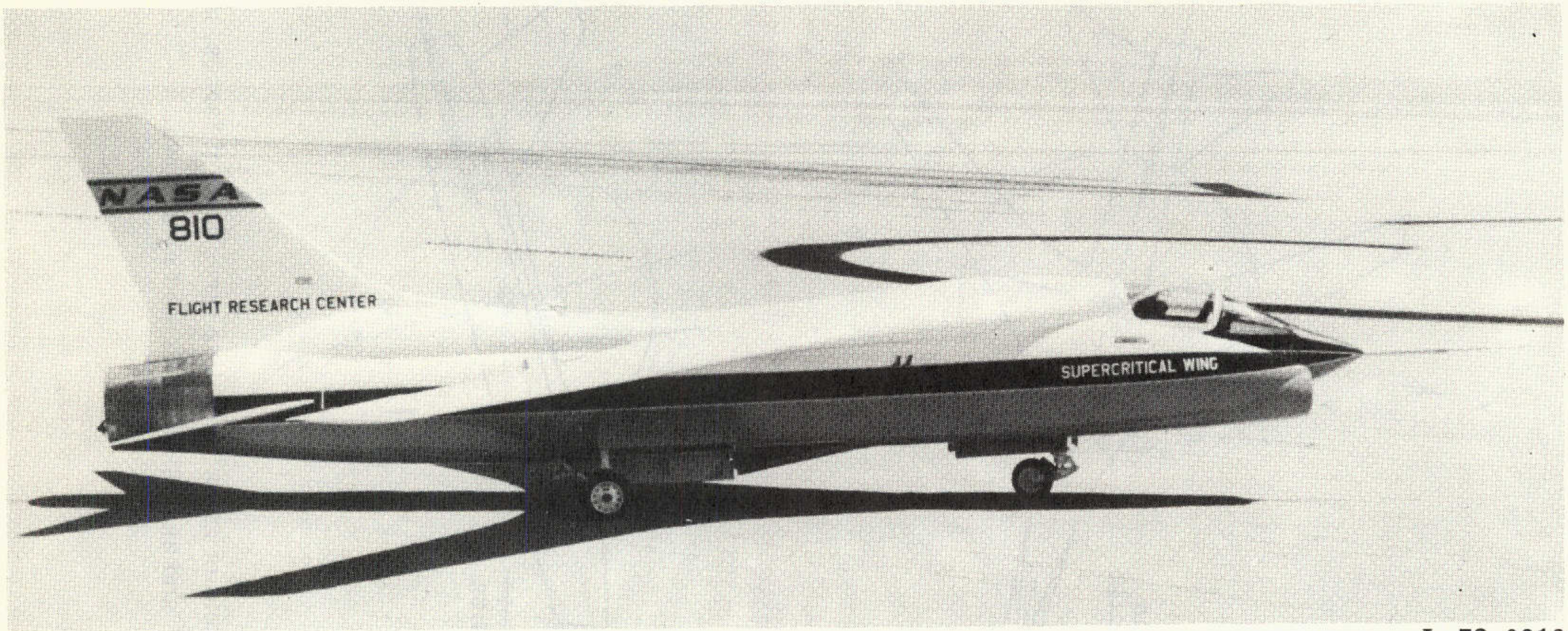

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Figure 2.- Photograph of aircraft for which derivatives were extracted.

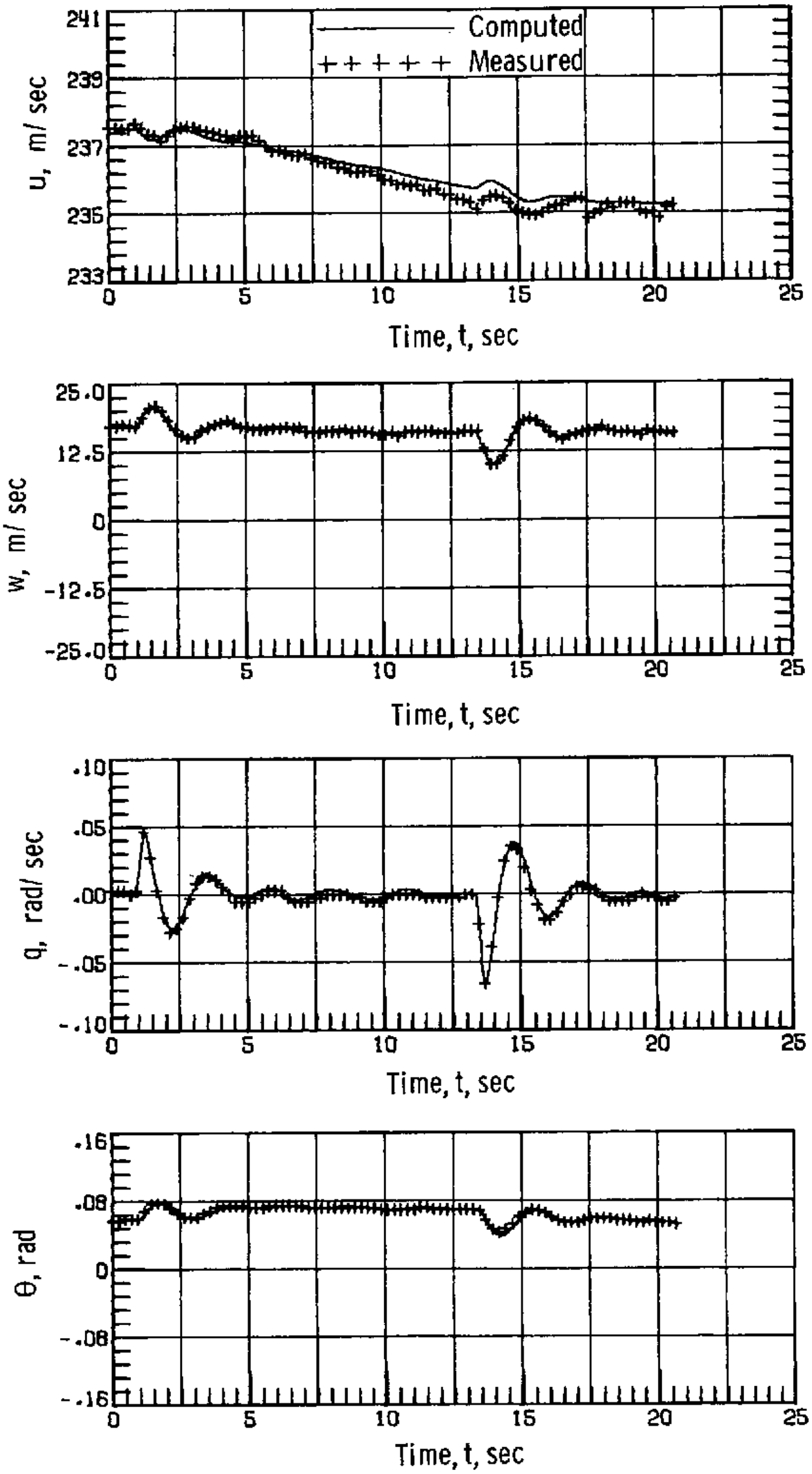


Figure 3.- Comparison of flight data with time histories computed by using the aerodynamic parameters of table IV for elevator input at Mach number 0.80.

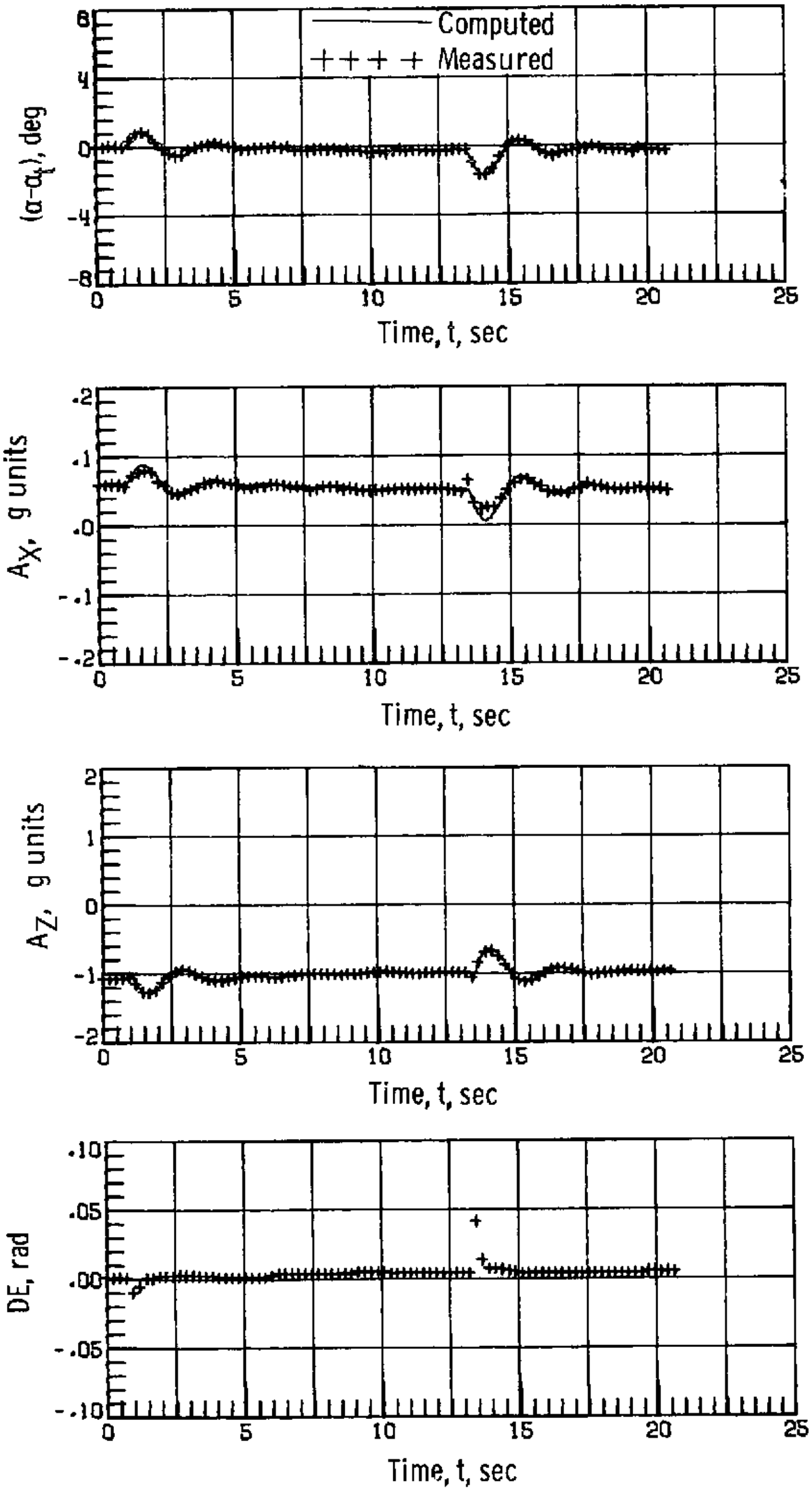


Figure 3.- Concluded.

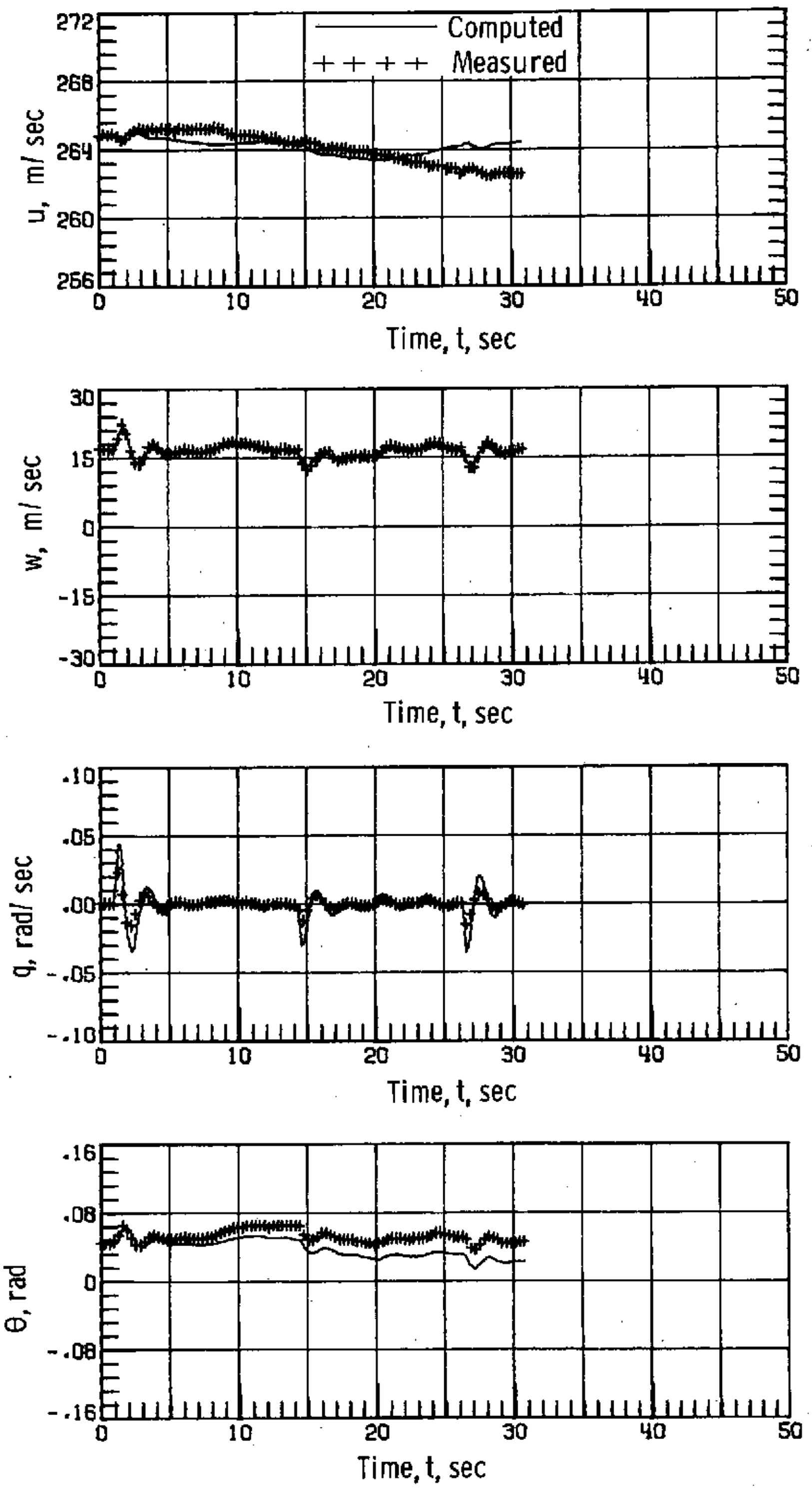


Figure 4.- Comparison of flight data with time histories computed by using the aerodynamic parameters of table IV for elevator input at Mach number 0.90.

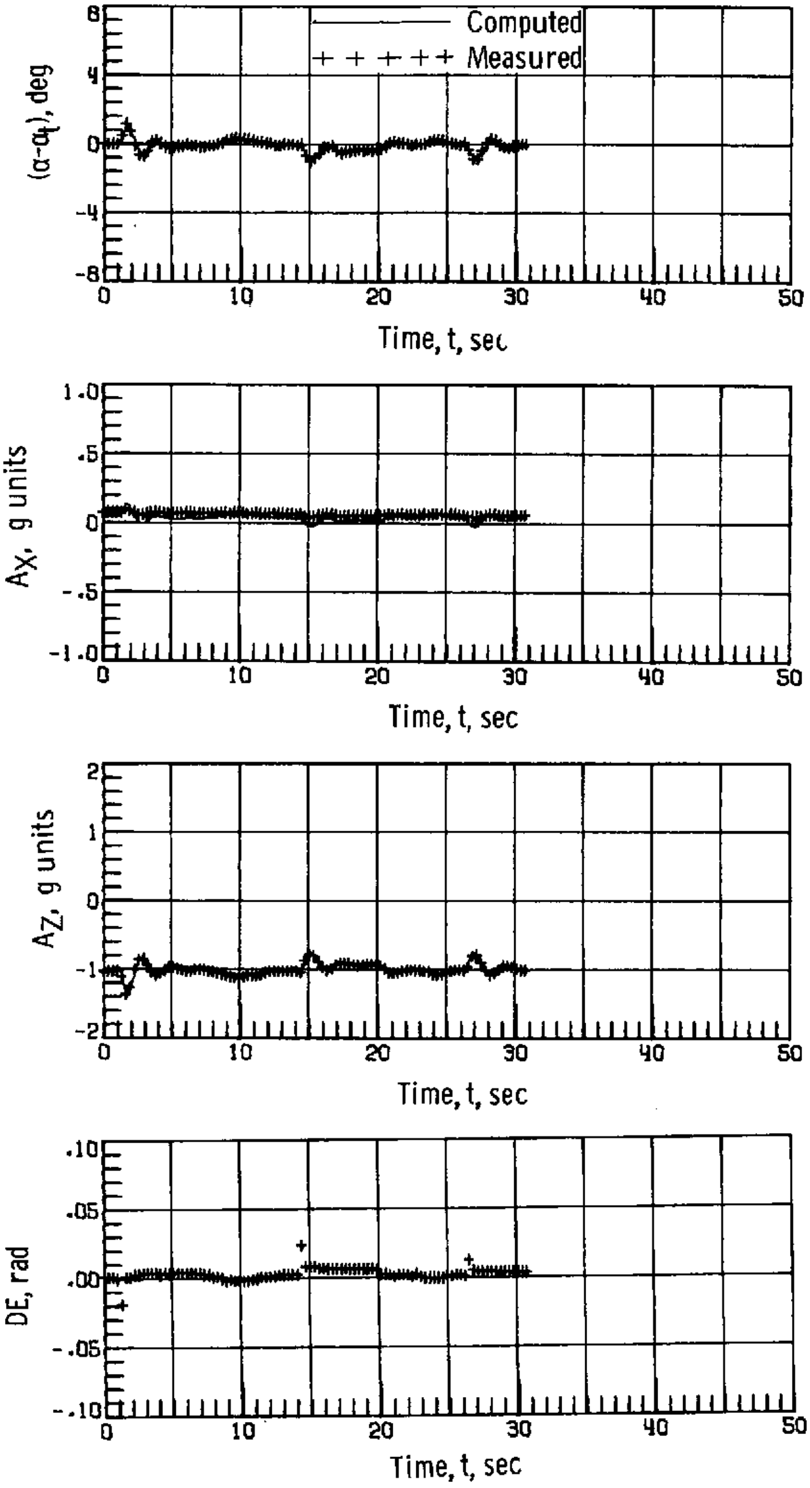


Figure 4.- Concluded.

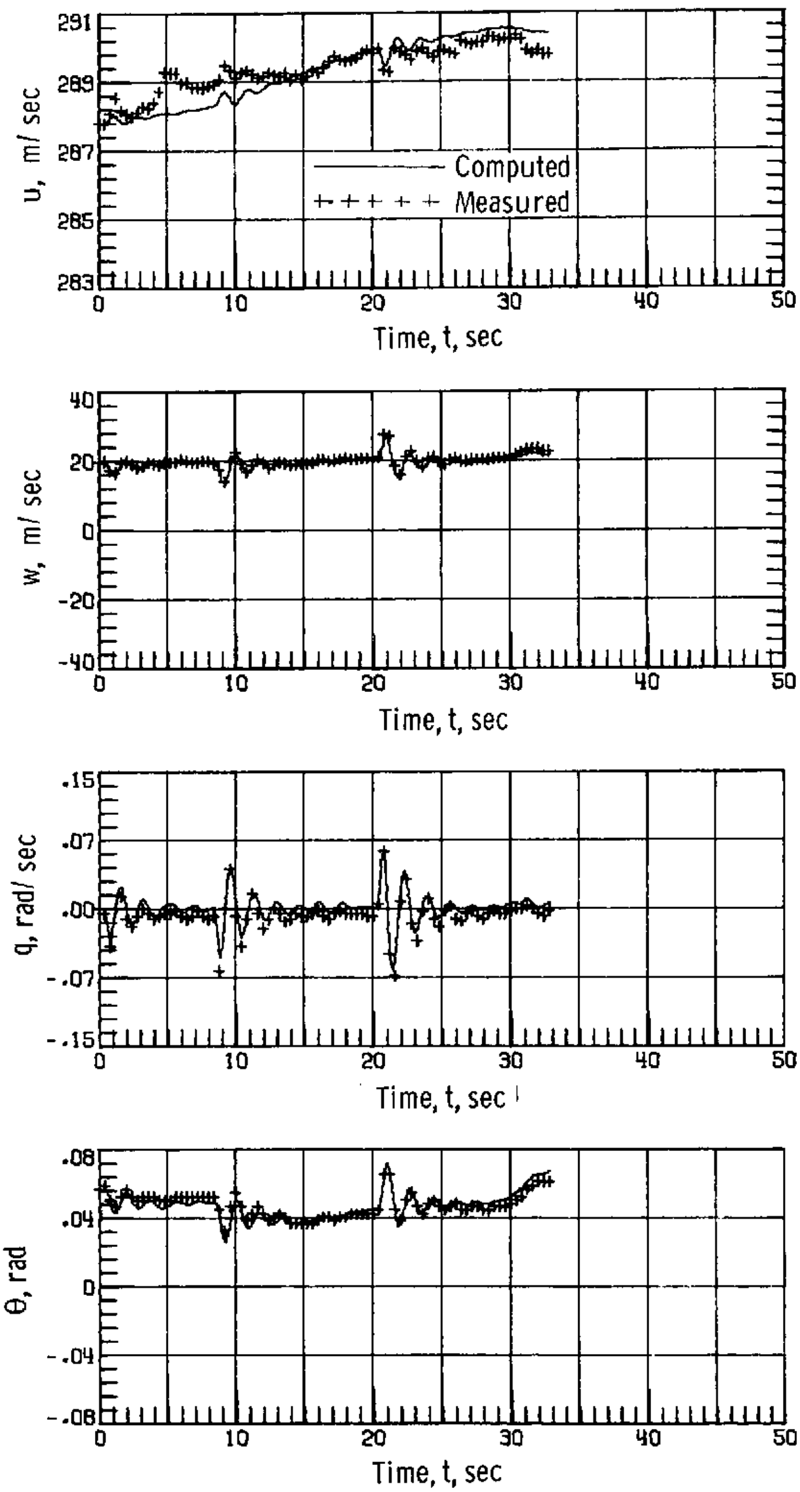


Figure 5.- Comparison of flight data with time histories computed by using the aerodynamic parameters of table IV for elevator input at Mach number 0.98.

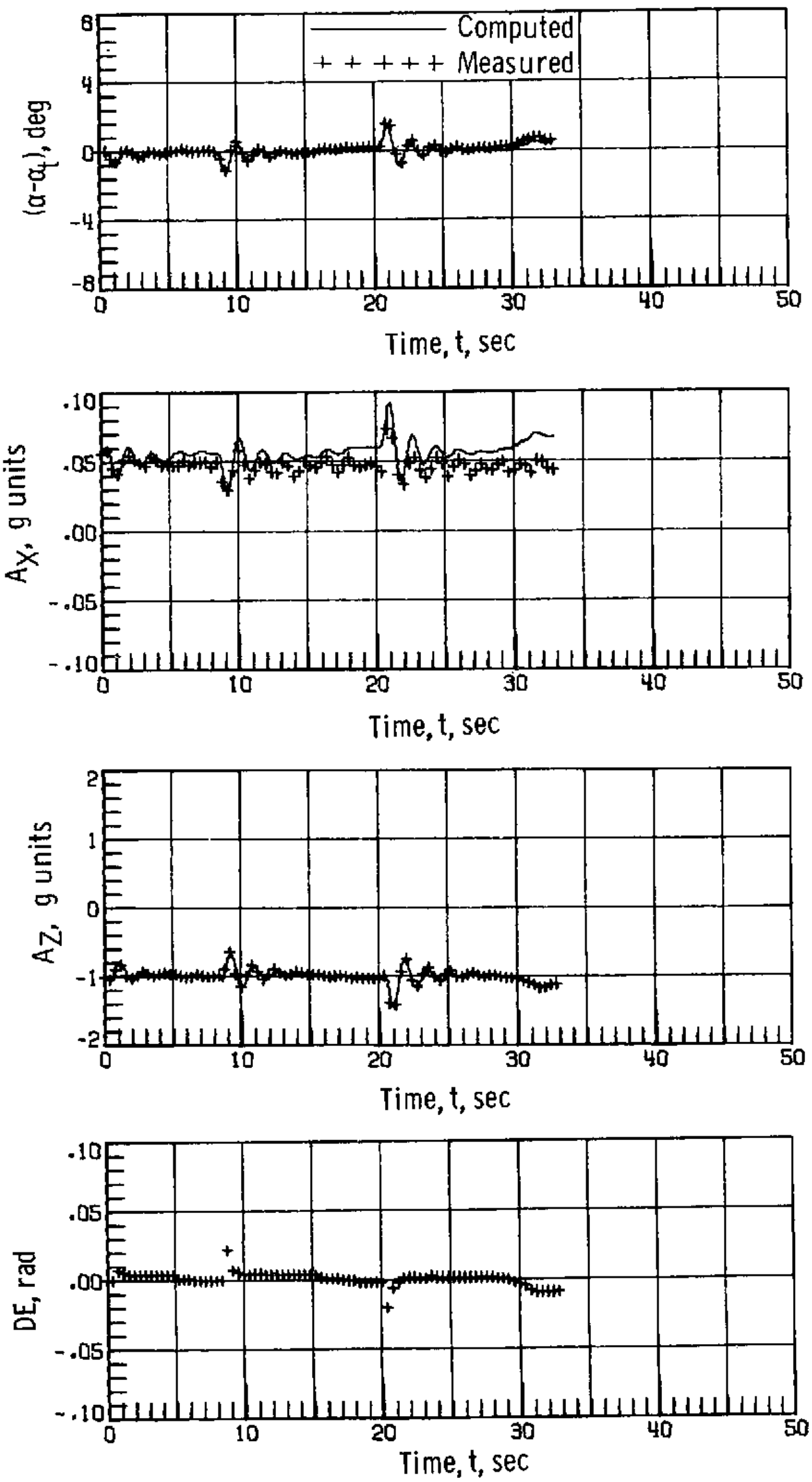
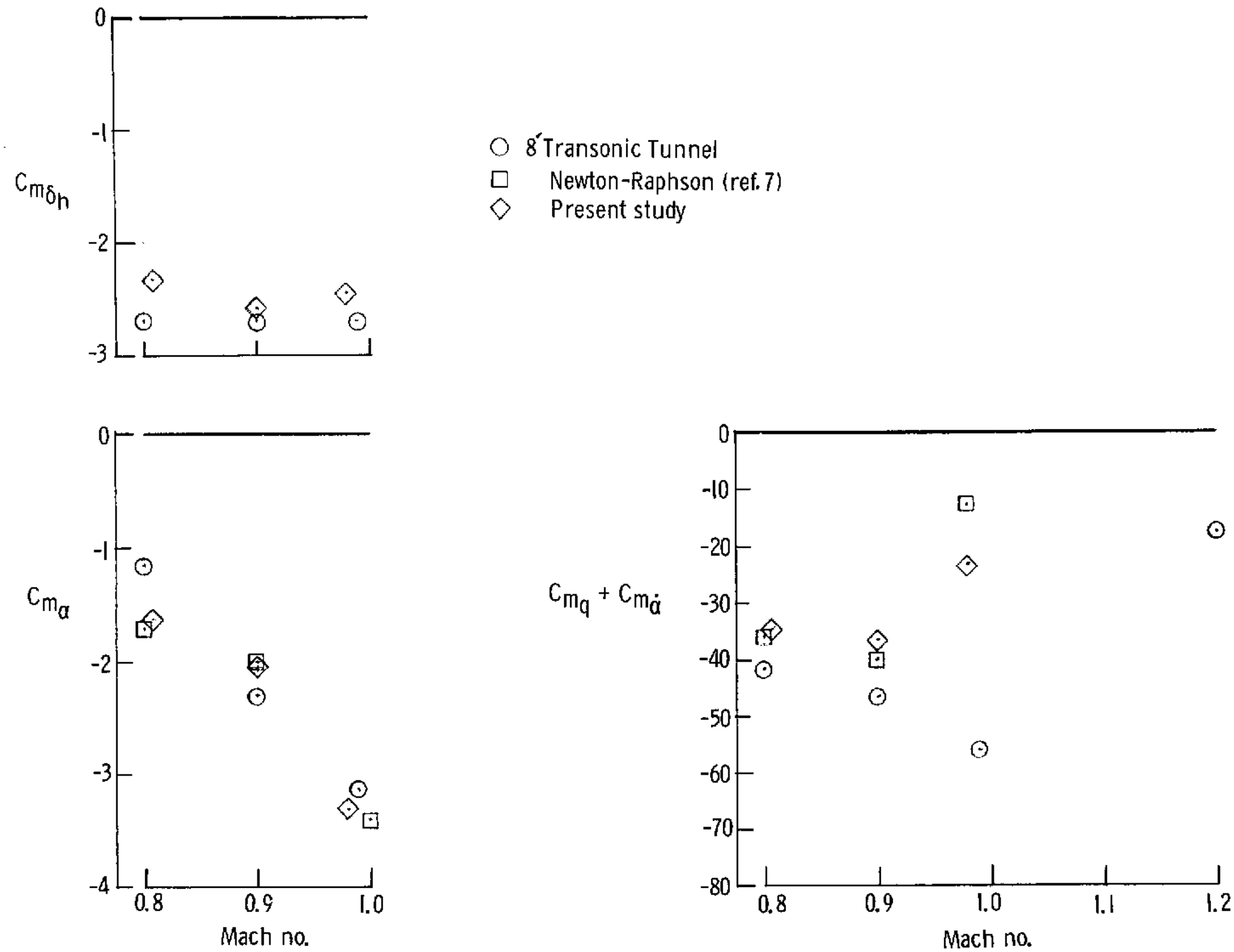
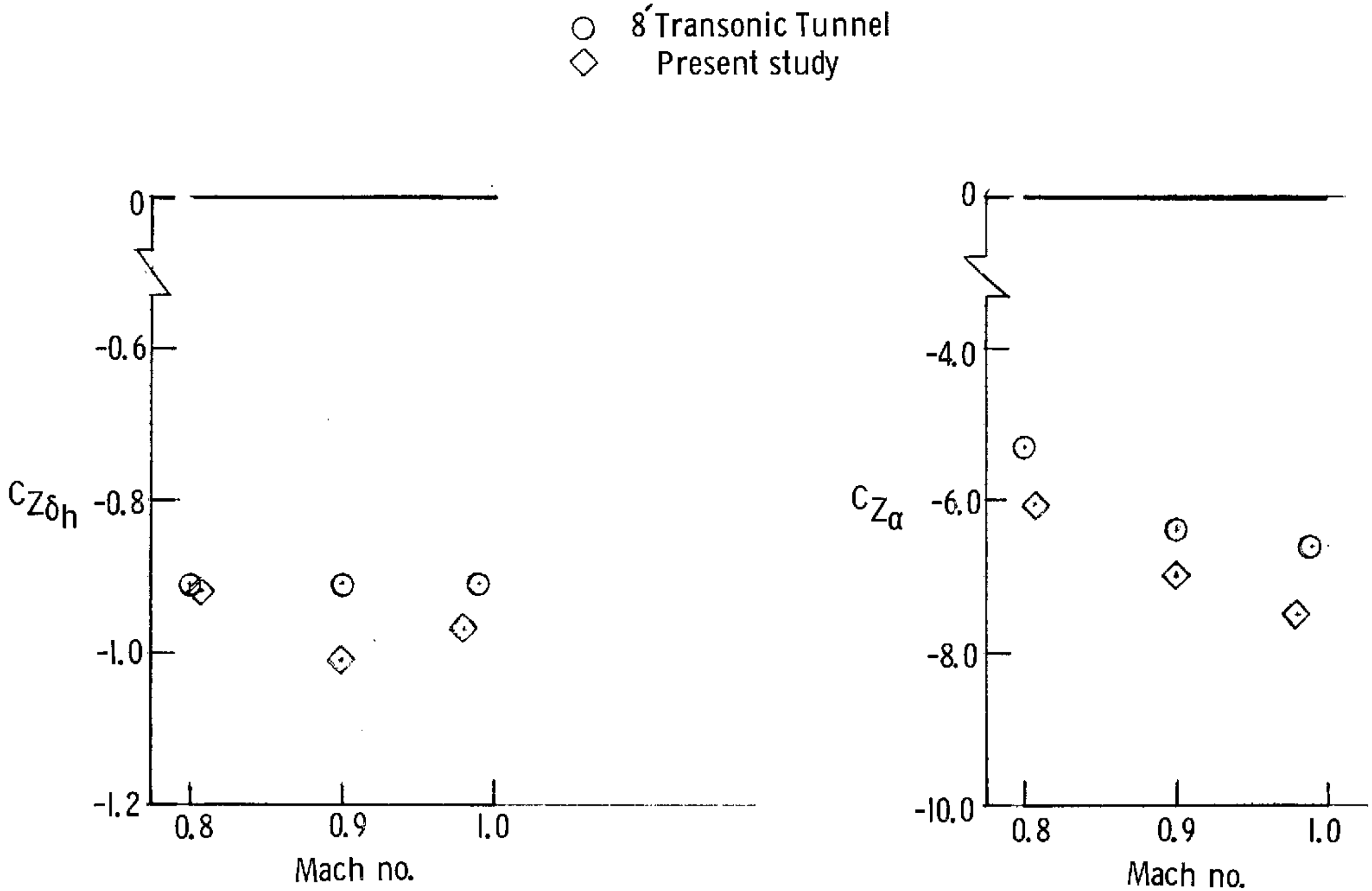


Figure 5.- Concluded.



(a) Pitching-moment derivatives.

Figure 6.- Comparison of extracted derivatives with Mach number for the F-8 supercritical-wing aircraft with preliminary results from the Langley 8-foot transonic pressure tunnel.



(b) Normal-force derivatives.

Figure 6.- Concluded.

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