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AEDC-TR-69-151

DYNAMIC TESTS OF A 10-DEG CONE HAVING THREE ANGULAR DEGREES OF FREEDOM AT MACH 8

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ARO, Inc.

September 1969

VON KÁRMÁN GAS DYNAMICS FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

DYNAMIC TESTS OF A 10-DEG CONE HAVING THREE ANGULAR DEGREES OF FREEDOM AT MACH 8

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FOREWORD

The work reported herein was sponsored by the Sandia Corporation, Sandia Base, Albuquerque, New Mexico, under authority of the Atomic Energy Commission (AEC) Order Number AL 67-255, Sub Order 012, and Air Force Systems Command (AFSC) Program 921D.

The results of tests presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), AFSC, Arnold Air Force Station, Tennessee, under Contract F40600-69-C-0001. The test was conducted on March 27, 1969, under ARO Project Number VB1892, and the manuscript was submitted for publication on June 6, 1969.

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This technical report has been reviewed and is approved.

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ABSTRACT

Dynamic stability data were obtained on a slightly blunted 10-deg half-angle cone at Mach number 8. The tests were conducted using a unique balance system which allowed the model to have three angular degrees of freedom. Both a symmetrical model and a model having compound configurational asymmetries were tested at free-stream Reynolds numbers, based on model length, of from 1.61×10^6 to 2.95×10^6. Data obtained on the symmetrical model at roll rates up to 300 rev/min showed the damping-in-pitch derivatives to be nearly constant with roll rate.

CONTENTS

ILLUSTRATIONS

TABLE

NOMENCLATURE

A	Reference area (model base area)
C_M	Pitching-moment coefficient of a model which has triagonal or greater symmetry (independent of model roll orientation)
$C_{M_{p\alpha}}$	$C_{M_{p\alpha}} = C_{m_{p\beta}} = C_{n_{p\alpha}}$, Magnus-moment coefficient
C_{M_q}	$C_{M_q} = C_{m_q} = C_{n_r}$, damping-in-pitch derivative coefficient
C_{M_α}	$C_{M_\alpha} = C_{m_\alpha} = -C_{n_\beta}$, slope of the pitching-moment coefficient curve
$C_{M_{\dot\alpha}}$	$C_{M_{\dot\alpha}} = C_{m_{\dot\alpha}} = -C_{n_{\dot\beta}}$, damping-in-pitch derivative coefficient
C_m	Pitching-moment coefficient, pitching moment/$q_\infty Ad$
$C_{m_{p\beta}}$	$\partial^2 C_m/\partial(Pd/2V_\infty)\partial\beta$
C_{m_q}	$\partial C_m/\partial(qd/2V_\infty)$
C_{m_α}	$\partial C_m/\partial\alpha$
$C_{m_{\dot\alpha}}$	$\partial C_m/\partial(\dot\alpha d/2V_\infty)$
C_n	Yawing-moment coefficient, yawing moment/$q_\infty Ad$
$C_{n_{p\alpha}}$	$\partial^2 C_n/\partial(Pd/2V_\infty)\partial\alpha$
C_{n_r}	$\partial C_n/\partial(rd/2V_\infty)$
C_{n_β}	$\partial C_n/\partial\beta$
$C_{n_{\dot\beta}}$	$\partial C_n/\partial(\dot\beta d/2V_\infty)$
d	Model base diameter
I	Transverse moment of inertia
I_X	Axial moment of inertia
$\tilde{K}_{n,p,t}$	Nutation, precession, and trim complex modal vectors

ℓ	Model length, 27.98 in.
M_∞	Free-stream Mach number
P	Roll rate
q	Pitch rate
q_∞	Free-stream dynamic pressure
Re_ℓ	Free-stream Reynolds number based on model length
r	Yaw rate
r_n/r_b	Ratio of model nose radius to base radius
t	Time
V_∞	Free-stream velocity
XYZ	Body coordinates (Fig. 2)
$\hat{X}\hat{Y}\hat{Z}$	Nonrolling body coordinates (Fig. 2)
$X_T Y_T Z_T$	Tunnel fixed coordinates (Fig. 2)
z_{cg}	Displacement of the model center of gravity from the axis of symmetry along the Z axis (Fig. 3)
Θ, Ψ, Φ	Angles of pitch, yaw, and roll (Fig. 1)
$\lambda_{n,p}$	Nutation and precession damping rates
$\tilde{\xi}$	Complex angle of attack $(\hat{\Theta} + i\hat{\Psi})$
$\omega_{n,p}$	Nutation and precession angular circular frequencies $(\omega_{trim} = \dot{\Phi})$

SUBSCRIPTS

E	Effective values
o	Quantity at reference condition $(\tilde{\xi} = 0)$

SUPERSCRIPTS

$\dot{}, \ddot{}$	First and second derivatives with respect to time
~	Complex quantities
^	Relative to nonrolling coordinates

SECTION I
INTRODUCTION

Research is being conducted by the Sandia Corporation to study the dynamic behavior of a slightly blunted ($r_n/r_b = 0.0156$) 10-deg half-angle cone. The research includes computer studies of six-degree-of-freedom motion, the present wind tunnel test program, and a full-scale flight test program.

The purpose of the present wind tunnel tests was to investigate the dynamic behavior of a conical model having three angular degrees of freedom. Both a symmetrical model and a model having compound asymmetries were tested using the von Kármán Gas Dynamics Facility (VKF) three-degree-of-freedom dynamic balance (Ref. 1). The compound asymmetries were obtained by offsetting the balance pivot point from the model centerline to a point in the XZ plane (See Figs. 1 and 2) and additionally rotating the principal inertia axes in the XY plane.

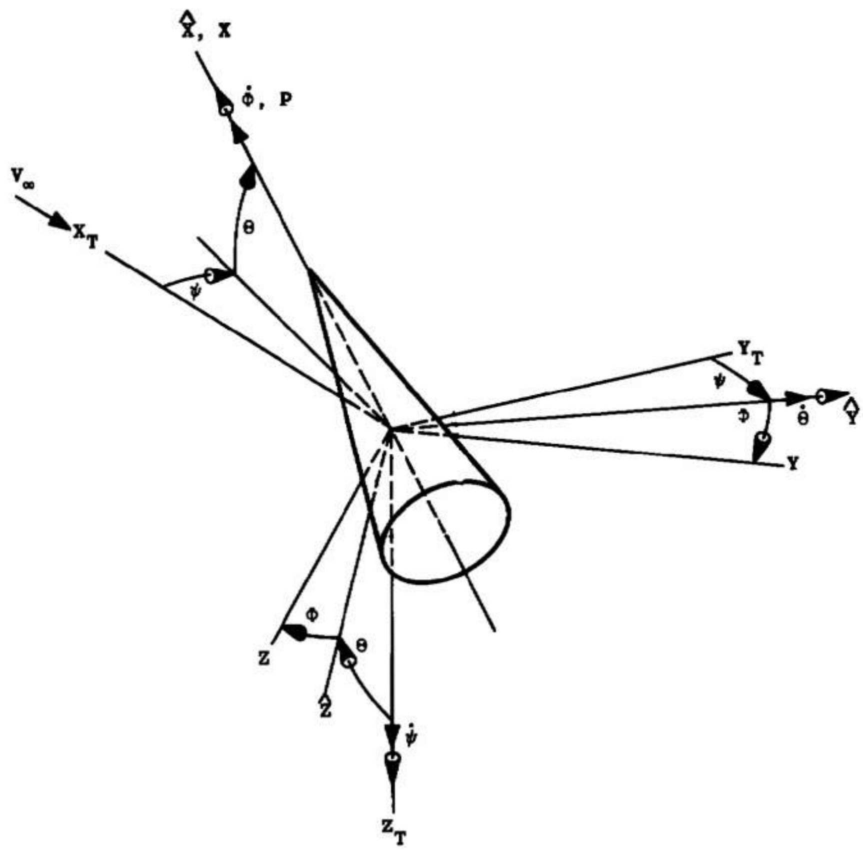


Fig. 1 Coordinate Systems

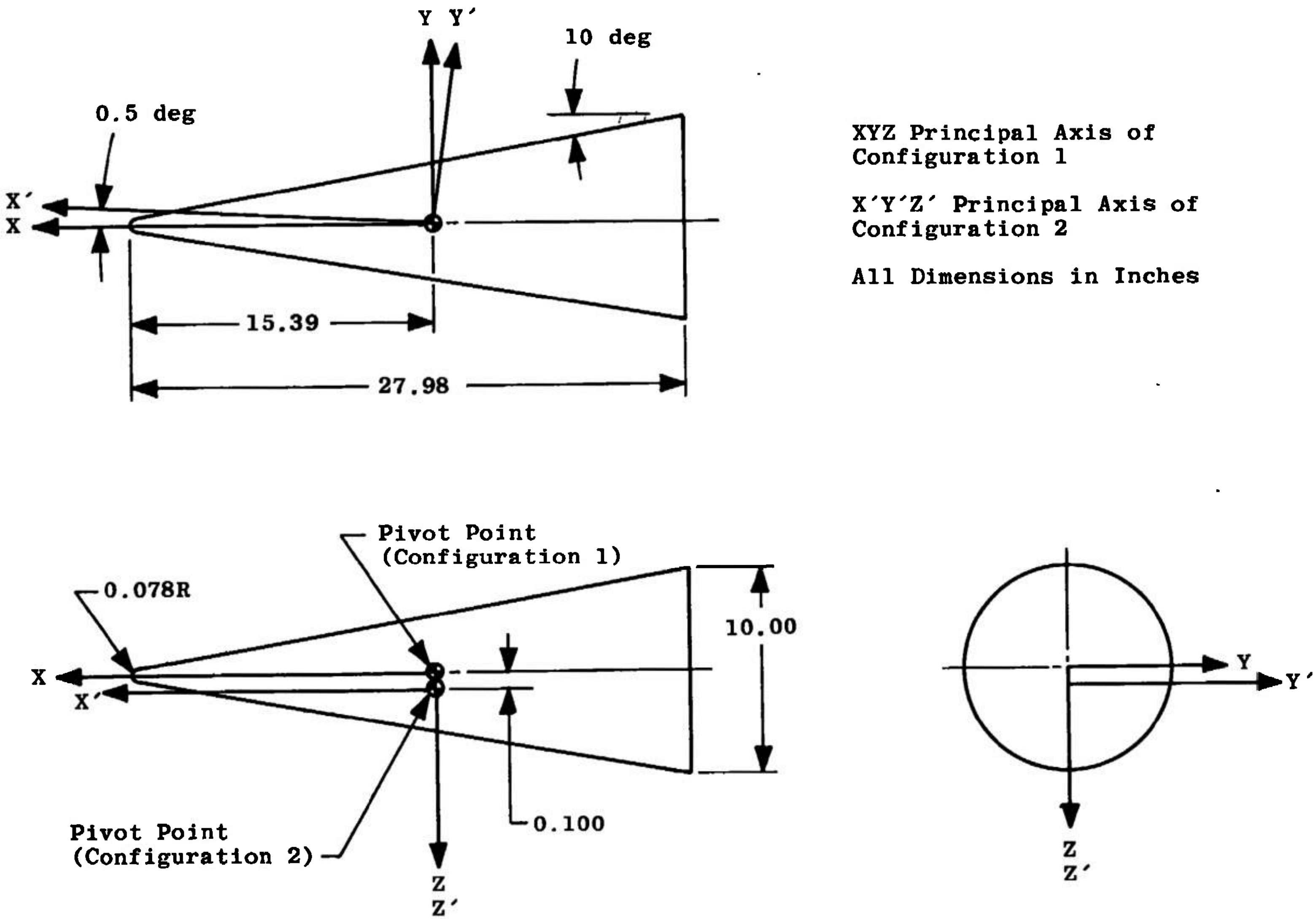


Fig. 2 Sketch of the Model

The test was conducted in the 50-in.-diam tunnel B (Gas Dynamic Wind Tunnel, Hypersonic (B)) of the VKF at a nominal free-stream Mach number of 8 and at free-stream Reynolds numbers, based on model length, of 2.92×10^6 and 1.61×10^6.

SECTION II
APPARATUS

2.1 THREE-DEGREE-OF-FREEDOM DYNAMIC BALANCE

A sketch of the balance assembly is shown in Fig. 3. The balance consists of a spherical gas bearing pivot, a three-axis variable reluctance angular transducer, a model release mechanism, and a model locking device. The spherical gas bearing provides a near-frictionless pivot which is desirable for dynamic stability testing at hypersonic speeds where it is necessary to minimize tare damping. The variable reluctance angular transducers provide continuous analog signals proportional to the angular displacements Θ and Ψ of the nonrolling axes (Fig. 1) and provide roll rate data. Models can be released from an initally pitched position with a yaw rate using the displacement arm and arm lock (Fig. 3). Both these initial conditions can be varied. The rotating arms are used to lock the model at zero angle of attack. The turbine and air jets are used to increase or decrease model roll rate when the model is in the locked position. These same air jets, when pulsed together, may be used to induce angular motion. A more detailed description of the balance system may be found in Ref. 1.

2.2 MODEL

The conical model (Figs. 2 and 4) was fabricated by the Sandia Corporation according to specifications supplied by the VKF. The model had a 10-in. base diameter, a 10-deg half-angle, and a nose-to-base bluntness ratio (r_n/r_b) of 0.0156. Provisions were made to add ballast fore and aft of the pivot point to allow both static and dynamic balancing. A sketch of the model (Fig. 2) shows that the model pivot point was located both on the centerline for Configuration 1 ($z_{cg}/d = 0$) and 0.100 in. off of the centerline ($z_{cg}/d = 0.01$) in the Z direction for Configuration 2 and at stations 55 percent aft from the model nose ($x_{cg}/\ell = 0.55$) for both configurations. These positions denote the location of the balance pivot point and, since the center-of-gravity of the model-balance system was also positioned at $x_{cg}/\ell = 0.55$, are henceforth termed the model center-of-gravity positions. Additionally, Configuration 2 had the principal inertia axes tilted approximately 0.5 deg in the body fixed XY plane as shown in Fig. 2. This axes tilt along with the offset center of gravity provided the compound configurational asymmetries.

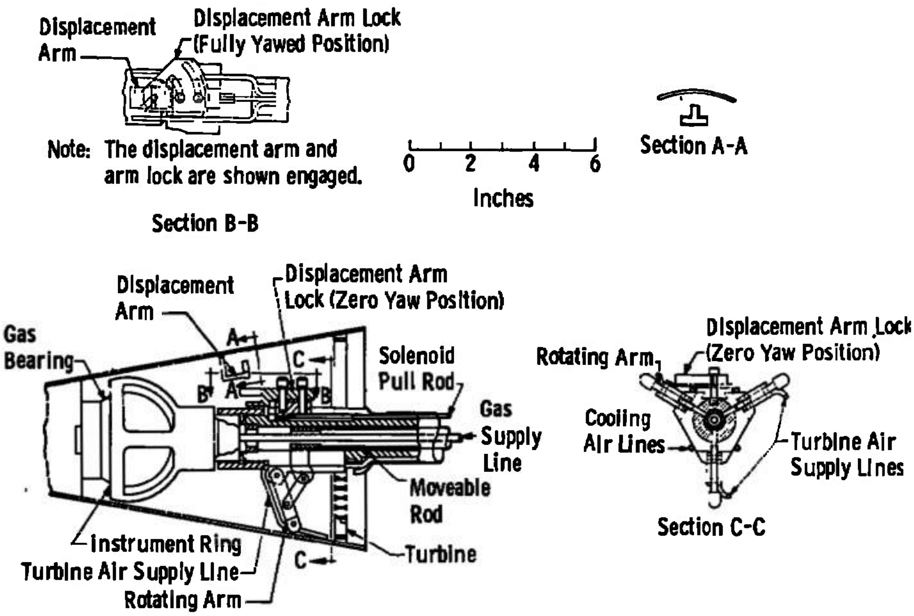
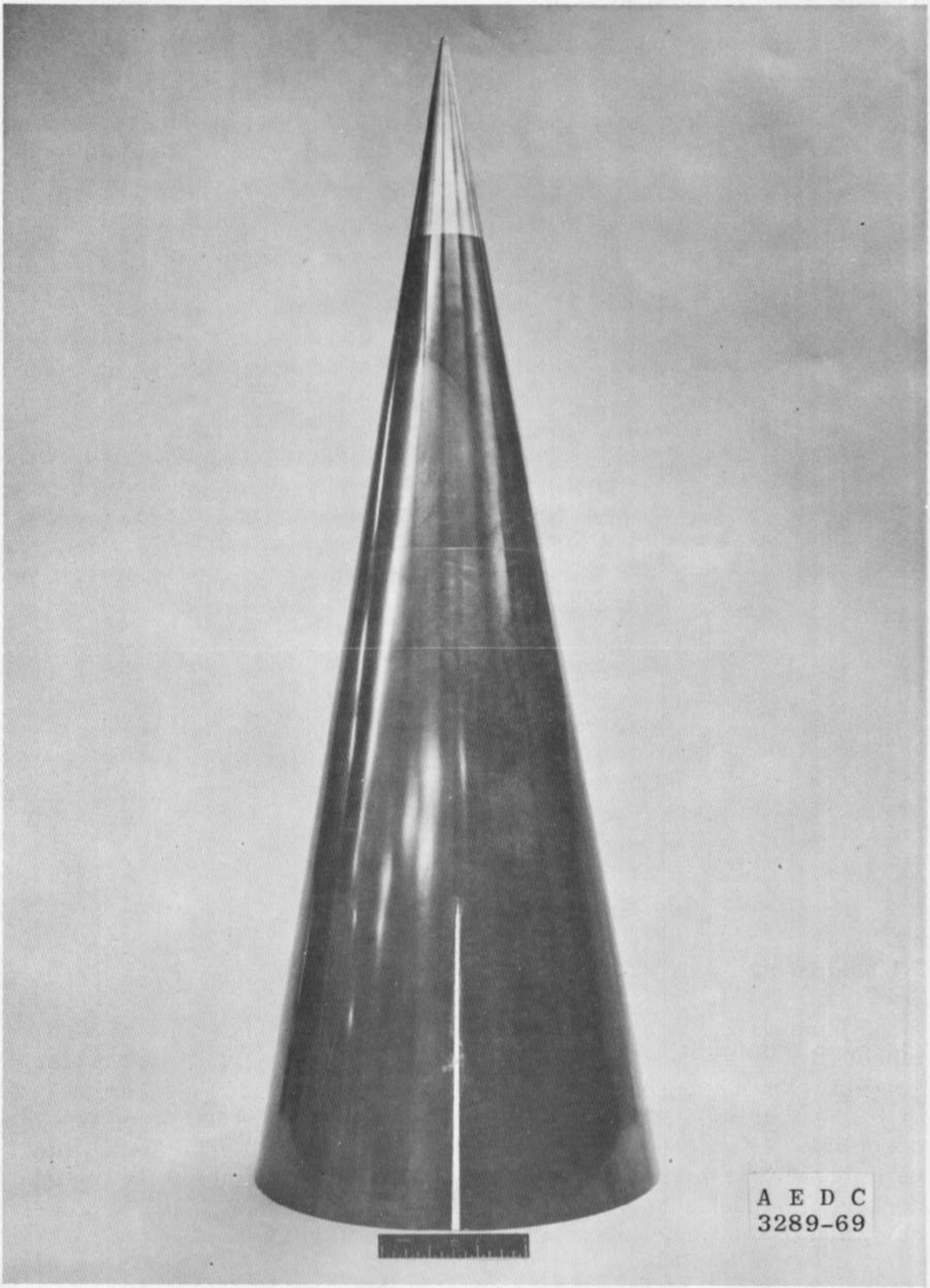


Fig. 3 Balance Assembly

2.3 WIND TUNNEL

Tunnel B is a continuous, closed-circuit, variable density wind tunnel with an axisymmetric contoured nozzle and a 50-in.-diam test section. The tunnel can be operated at a nominal Mach number of 6 or 8 at stagnation pressures from 20 to 300 and 50 to 900 psia, respectively, at stagnation temperatures up to 1350°R. The model may be injected into the tunnel for a test run and then retracted for model cooling or model changes without interrupting the tunnel flow. A description of the tunnel may be found in Ref. 2.



Fig, 4 Photograph of the Model

SECTION III
PROCEDURE

3.1 TUNNEL TESTS

A typical test run procedure was to inject the model into the test section tank and release it at the required initial conditions. After the desired amount of data had been obtained, the model was locked and retracted into the test section tank. At this point the model was cooled internally by directing cooling air on the model-balancing mounting bulkhead and externally by the standard test section tank model nose cooling system.

During the data-taking interval the analog signals, provided by the angular transducers, are simultaneously recorded on an analog tape and input directly to an analog-to-digital converter for storage on magnetic tape. The digital data are then input to the VKF digital computer for final data reduction. A summary of the test conditions is given in Table I.

TABLE I
TEST CONDITIONS

Wind Tunnel Test Conditions

Configuration No.	M_∞	$Re_\ell \times 10^{-6}$	Stilling Chamber Pressure, psia	Stilling Chamber Temperature, °R	q_∞, psia	V_∞, ft/sec
1	7.90	1.61	125	1170	87.8	3606
2	7.95	2.95	250	1235	169.9	3709

Model Parameters

Configuration No.	x_{cg}/ℓ	z_{cg}/d	r_n/r_b	I_X, slug-ft^2	I_Y, slug-ft^2	I_Z, slug-ft^2
1	0.55	0	0.0156	0.0416	0.2686	0.2686
2	0.55	0.01	0.0156	0.0464	0.2874	0.2877

3.2 DATA REDUCTION

The data were reduced using the linear tricyclic theory in nonrolling coordinates as developed originally by Nicolaides in Ref. 3. The equation of a model suspended in an airstream and restricted to three angular degrees of freedom about a point fixed in space is noted as

$$\ddot{\tilde{\xi}} + [G + iH]\dot{\tilde{\xi}} + [J + iK]\tilde{\xi} = Le^{i\nu t} \quad (1)$$

where

$$G = -\frac{q_\infty Ad^2}{2V_\infty I}(C_{M_q} + C_{M_{\dot{\alpha}}})$$

$$H = -\frac{I_x}{I}P$$

$$J = -\frac{q_\infty Ad}{I}C_{M_\alpha}$$

$$K = -\frac{q_\infty Ad^2}{2V_\infty I}C_{M_{p\alpha}}P$$

$$L = \frac{i\, q_\infty Ad}{I}(C_{m_o} + i\, C_{n_o})$$

$$i = \sqrt{-1}$$

The tricyclic solution to Eq. (1) is given in Ref. 3 as

$$\tilde{\xi} = \tilde{K}_n e^{(\lambda_n + i\omega_n)t} - \tilde{K}_p e^{(\lambda_p + i\omega_p)t} + \tilde{K}_t e^{iPt} \qquad (2)^*$$

where

$$K_n = \frac{\dot{\tilde{\xi}} - (\lambda_p - i\omega_p)(\tilde{\xi}_o - K_t)}{\lambda_n - \lambda_p + i(\omega_n - \omega_p)}$$

$$K_p = \frac{\dot{\tilde{\xi}} - (\lambda_n - i\omega_n)(\tilde{\xi}_o - K_t)}{\lambda_p - \lambda_n + i(\omega_p - \omega_n)}$$

---

*The subscripts n and p, denoting nutation and precession, are used only as a convenient notation. The nutation arm is identified after fitting the data as the arm (K) having the largest absolute frequency $(|\omega_n| > |\omega_p|)$ and the same rotational direction as the roll rate.

$$K_t = \frac{L}{(P - \omega_n)(P - \omega_p) + \lambda_n \lambda_p + i[\lambda_n (P - |\omega_p) + \lambda_p (P - \omega_n)]}$$

$$\lambda_{n,p} \pm i\,\omega_{n,p} = -\frac{(G + iH) \pm \sqrt{G^2 - i2GH - H^2 - 4(J - iK)}}{2}$$

The model damping rates (λ_n, λ_p) and angular frequencies (ω_n, ω_p) are obtained by fitting Eq. (2) plus a constant complex vector to the model displacement-time history using a least-squares differential correction method. The solution is "fitted" over short overlapping segments of the displacement-time history. Once the model damping rates and frequencies have been determined, the aerodynamic coefficients may be obtained using the following relationships:

$$C_{M_q} + C_{M_{\dot{\alpha}}} = \frac{2 V_\infty I}{q_\infty A d^2} \cdot (\lambda_n + \lambda_p)$$

$$C_{M_\alpha} = \frac{I}{q_\infty A d^2} (\omega_n \omega_p - \lambda_n \lambda_p)$$

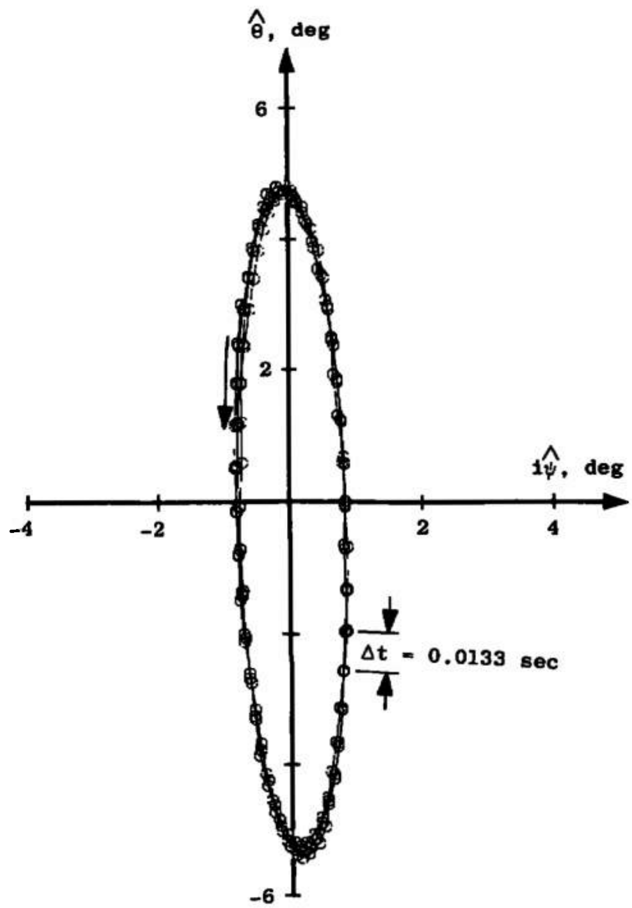
$$C_{M_{p\alpha}} = -\frac{2 V_\infty I}{q_\infty A d^2} \frac{1}{P} (\lambda_n \omega_p + \lambda_p \omega_n)$$

SECTION IV
RESULTS AND DISCUSSION

All data were obtained at a nominal Mach number of 8 (Table I). Only representative data obtained from the symmetrical model (Configuration 1) are presented; the analysis of the results obtained on Configuration 2 will be published at a later date by the Sandia Corporation.

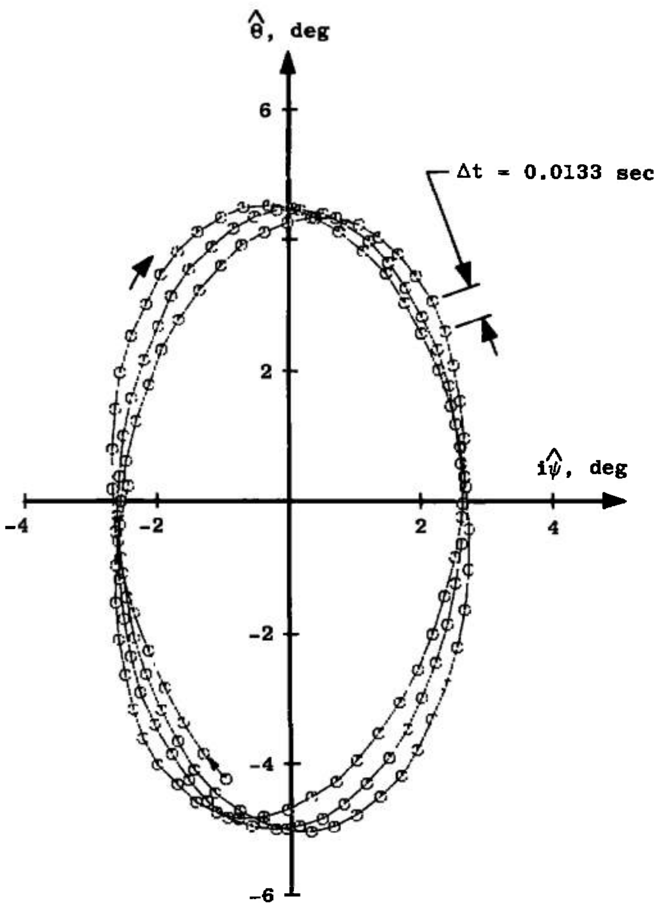
The tests were conducted at Reynolds numbers which were low enough to provide a laminar boundary layer over the full length of the model. Previous experience with conical models (Refs. 4 and 5) at hypersonic speeds has shown the damping derivatives to be higher when the model boundary layer is partially laminar or partially turbulent than when a laminar or near fully turbulent boundary layer exists on the model. Data obtained under the latter conditions are thought to be representative of a larger portion of the vehicle reentry trajectory.

Typical motion patterns obtained from the symmetrical model for various spin rates are shown in Fig. 5. These data indicate the uniformity with which the motion may be defined as the symbols represent only every tenth data point obtained.

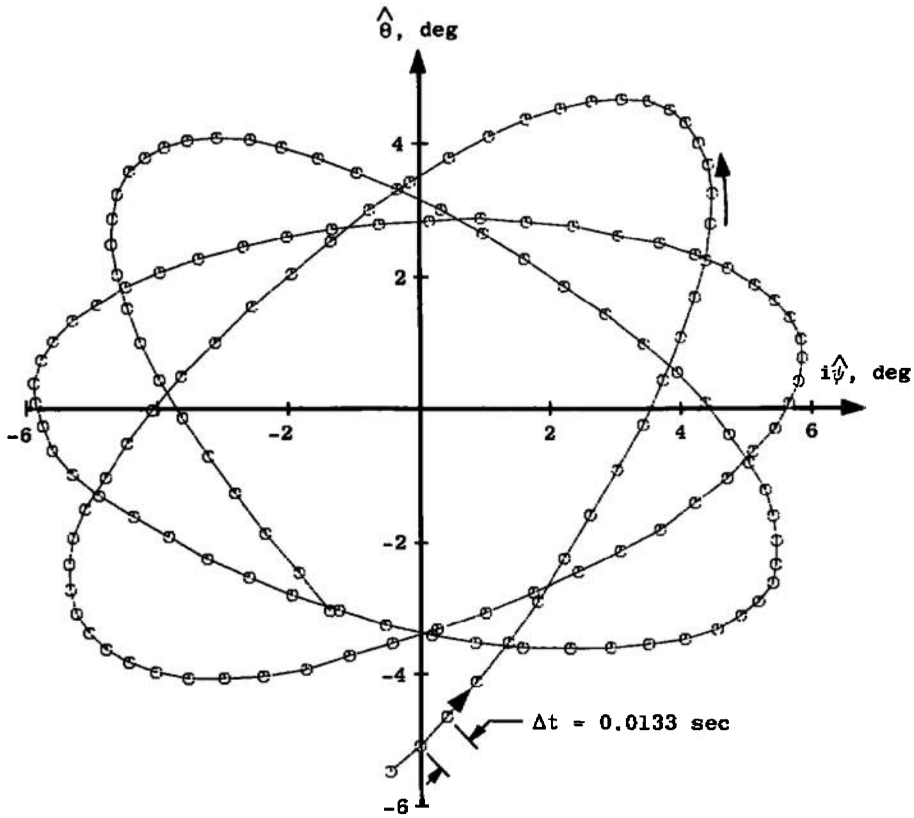


a. P ≈ 0

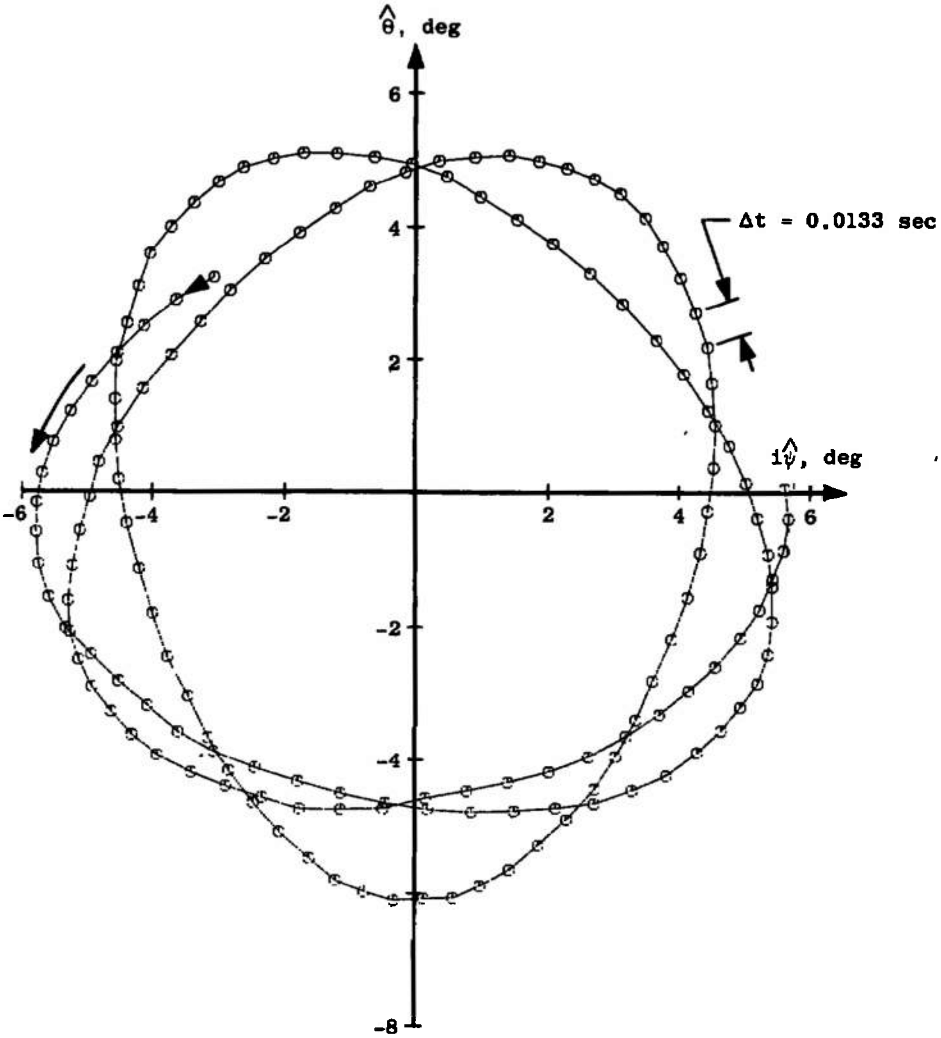
Fig. 5 Typical Motion Patterns from Configuration 1, M_∞ = 7.9, Re_ℓ = 1.61×10^6



b. P = 23 rpm
Fig. 5 Continued

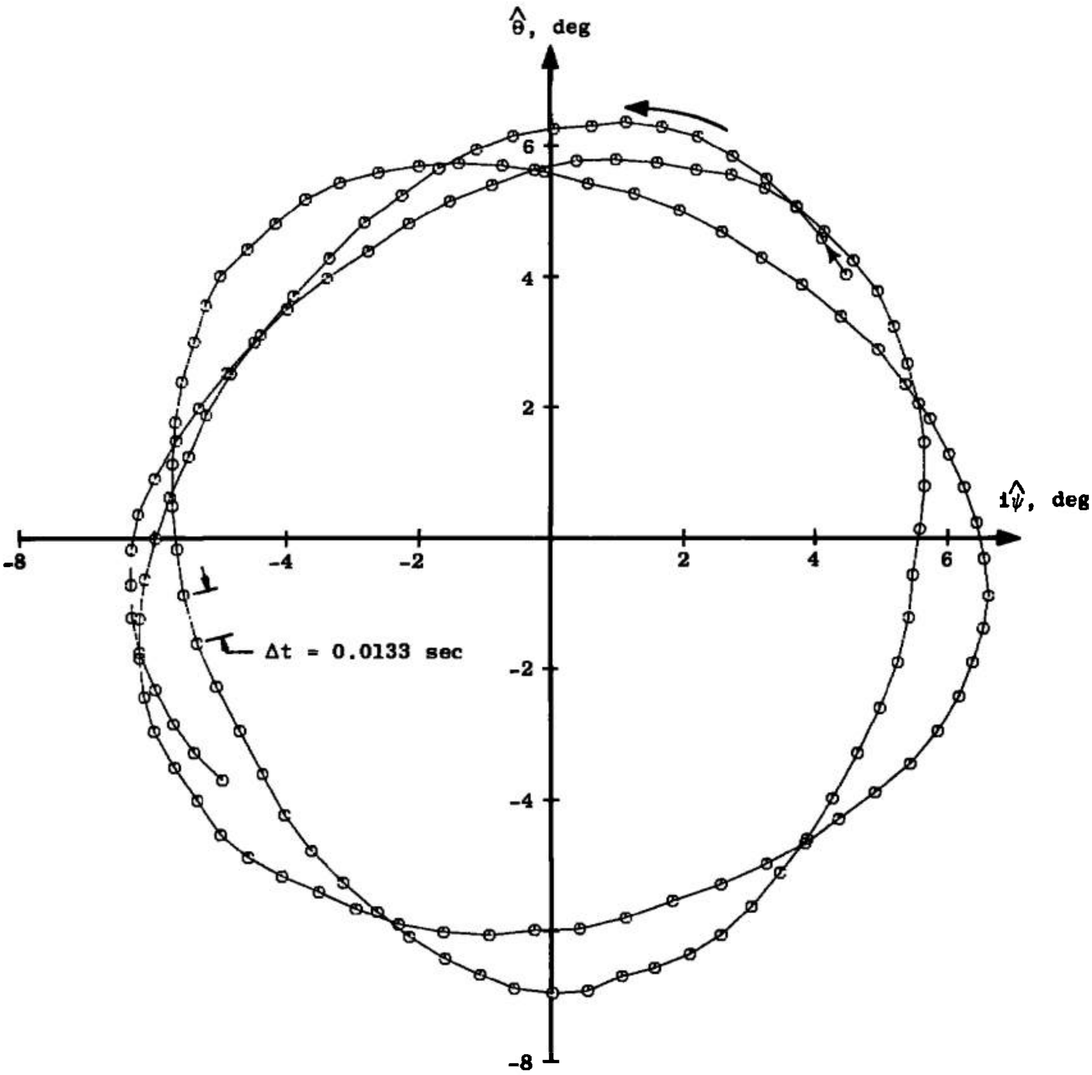


c. P = 126 rpm
Fig. 5 Continued

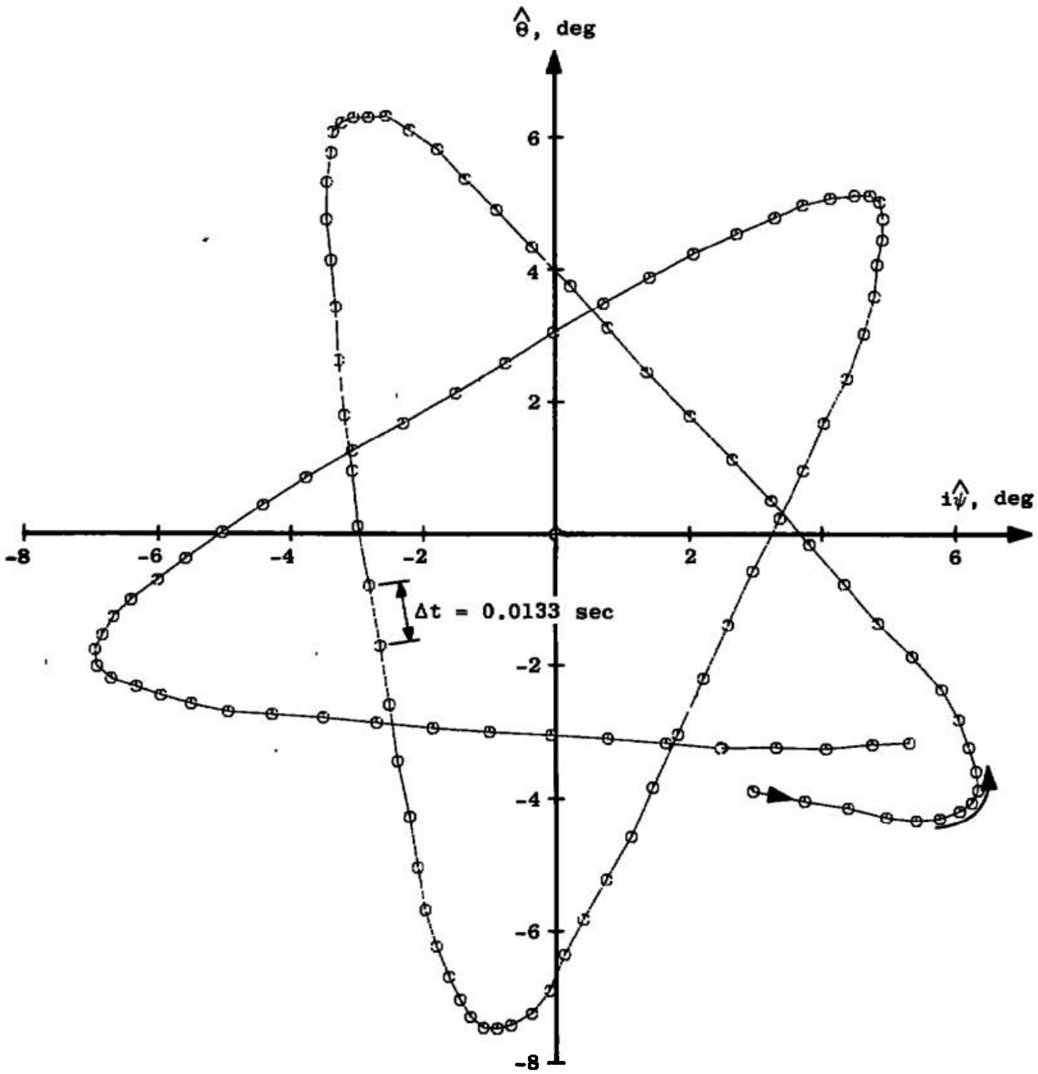


d. P = 214 rpm

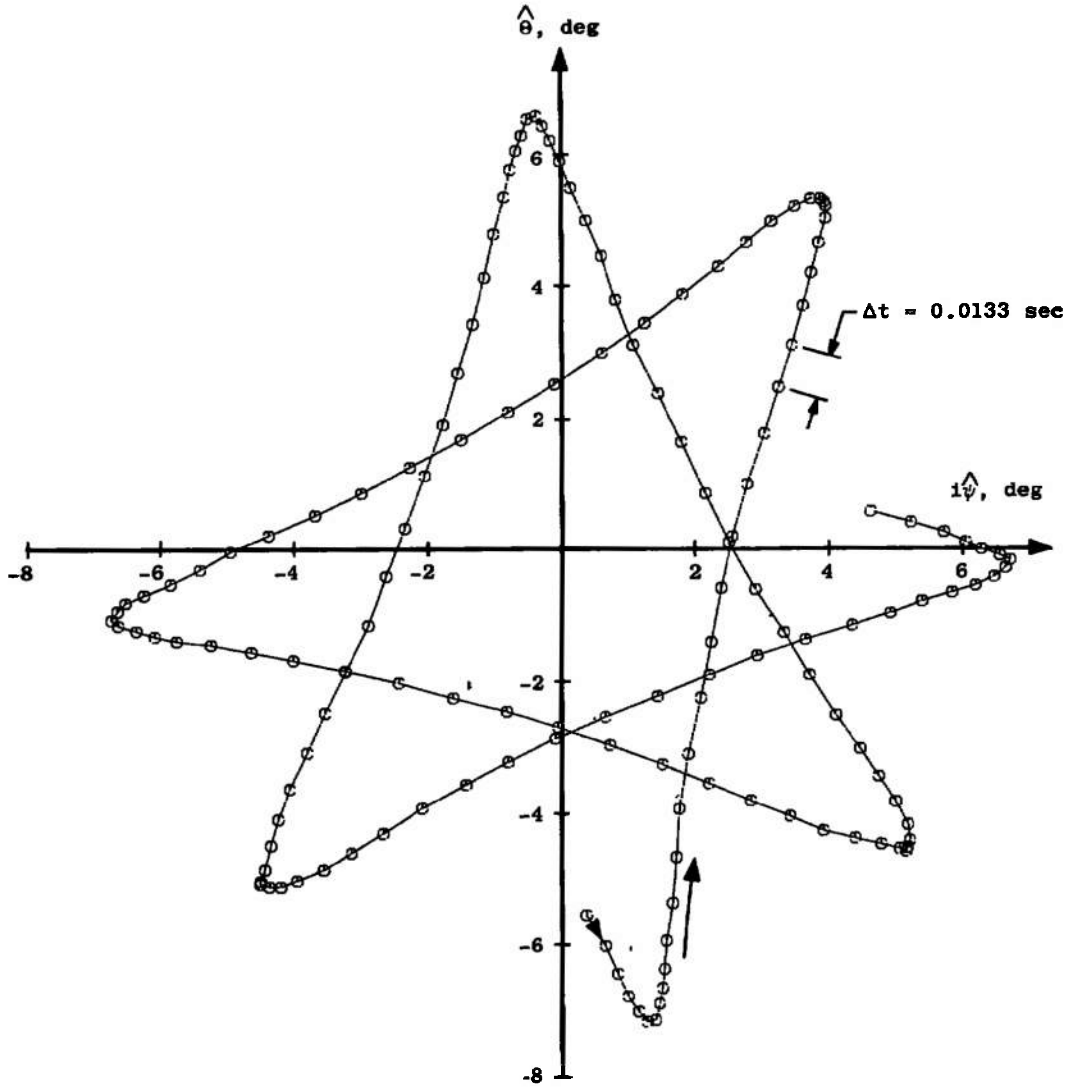
Fig. 5 Continued



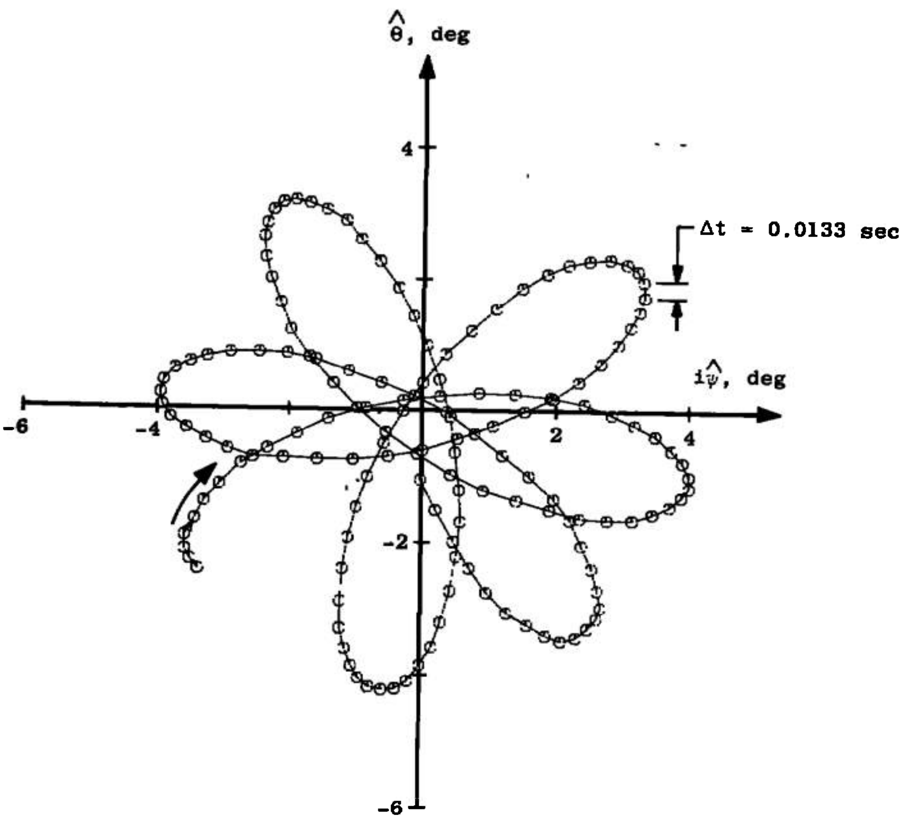
e. P = 271 rpm
Fig. 5 Continued



f. P = 225 rpm
Fig. 5 Continued



g. P = 313 rpm
Fig. 5 Continued



h. P = 236 rpm
Fig. 5 Concluded

The static and dynamic derivatives (C_{M_α} and $C_{M_q} + C_{M_{\dot{\alpha}}}$) are shown in Fig. 6 as a function of $Pd/2V_\infty$ (also P in rev/min). The derivatives were evaluated for a mean oscillation amplitude of 5 deg. No effect of $Pd/2V_\infty$ was noted for C_{M_α}; however, as may be seen in the figure, $C_{M_q} + C_{M_{\dot{\alpha}}}$ appeared to decrease slightly with increasing $Pd/2V_\infty$. The data are compared with the unsteady flow field theory of Brong (Ref. 6). The experimental values obtained for C_{M_α} agree quite well with the theory (Brongs' results yield the same value as the Stone-Kopal results). The damping derivatives are, however, somewhat lower than the theory.

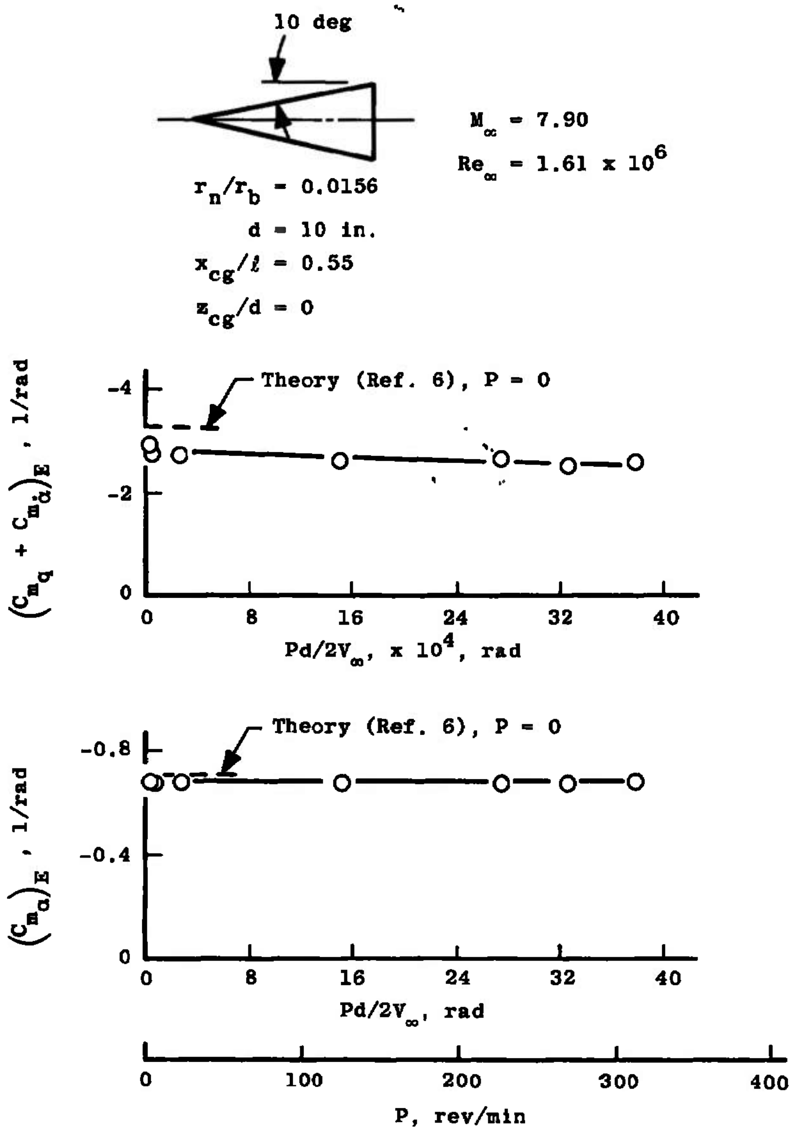


Fig. 6 Static and Dynamic Derivatives as a Function of $Pd/2V_\infty$, Configuration 1, Mean Oscillation Amplitude ≈ 5 deg

SECTION V
CONCLUSIONS

Wind tunnel tests at $M_\infty = 8$ were conducted using a dynamic balance having three angular degrees of freedom. Data obtained on a symmetrical 10-deg half-angle cone ($r_n/r_b = 0.0156$, $x_{cg}/\ell = 0.55$) at $Re_\ell = 1.16 \times 10^6$ showed the static stability parameter, C_{M_α}, to be invariant with model roll rate ($0 < P < 313$ rev/min) and the damping derivatives, $C_{M_q} + C_{M_{\dot{\alpha}}}$, to decrease slightly with increasing roll rate.

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UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Arnold Engineering Development Center ARO, Inc., Operating Contractor Arnold Air Force Station, Tennessee	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP N/A

3. REPORT TITLE

DYNAMIC TESTS OF A 10-DEG CONE HAVING THREE ANGULAR DEGREES OF FREEDOM AT MACH 8

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report March 27, 1969

5. AUTHOR(S) (First name, middle initial, last name)

L. K. Ward, Jr., and A. C. Mansfield, ARO, Inc.

6. REPORT DATE September 1969	7a. TOTAL NO. OF PAGES 25	7b. NO. OF REFS 6

8a. CONTRACT OR GRANT NO. F40600-69-C-0001 b. AFSC Program 921D c. AEC Order AL67-255, d. Sub Order 012	9a. ORIGINATOR'S REPORT NUMBER(S) AEDC-TR-69-151 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) N/A

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11. SUPPLEMENTARY NOTES Available in DDC.	12. SPONSORING MILITARY ACTIVITY Atomic Energy Commission P. O. Box 5400 Albuquerque, New Mexico 87115

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Wind Tunnel tests						
hypersonic flow						
cones						
dynamic stability characteristics						

1. Cones -- Stability

2. " -- Hypersonic flow

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