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DYNAMIC STABILITY CHARACTERISTICS OF A 10-DEG CONE AT LARGE AMPLITUDES OF OSCILLATION AT MACH NUMBER 10

B. L. Uselton and J. H. Gregson

ARO, Inc.

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VON KÁRMÁN GAS DYNAMICS FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
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NOTICES

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FOREWORD

The work reported herein was done at the request of the Air Force Flight Dynamics Laboratory (AFFDL), Air Force Systems Command (AFSC), for the General Electric Missile and Space Division (GE-MSD), under Program Element 62405364, Project 8219, Task 821902.

The results of the tests presented were obtained by ARO, Inc. (a subsidiary of Sverdrup and Parcel, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), AFSC, Arnold Air Force Station, Tennessee, under Contract AF40(600)-1200. The tests were conducted under ARO Project No. VT0357 during the periods from June 30 to July 2, 1965, and on December 16, 1965. The manuscript was submitted for publication on February 11, 1966.

This technical report has been reviewed and is approved.

John W. Hitchcock
Major, USAF
AF Representative, VKF
DCS/Test

Jean A. Jack
Colonel, USAF
DCS/Test

ABSTRACT

Tests were conducted in the 50-in. Mach 10 wind tunnel of the von Kármán Gas Dynamics Facility to determine the dynamic stability characteristics of a 10-deg half-angle cone at large amplitudes of oscillation. Support interference effects were also investigated. A free oscillation, high-amplitude (±35 deg) gas bearing balance supported by a transverse rod and yoke system was used. Data were obtained at a nominal Mach number of 10 at Reynolds numbers, based on the model base diameter, ranging from 0.46×10^6 to 1.84×10^6. The dynamic and static stability data are compared with data obtained with a sting-supported model, range data, flow field theory, and conical flow theory. Selected test results are presented.

CONTENTS

ILLUSTRATIONS

TABLE

NOMENCLATURE

A	Reference area (model base area), ft^2
C_m	Pitching-moment coefficient, pitching moment/$q_\infty Ad$
C_{m_q}	$\partial C_m/\partial(qd/2V_\infty)$ } Damping-in-pitch derivatives, 1/rad
$C_{m_{\dot{\alpha}}}$	$\partial C_m/\partial(\dot{\alpha}d/2V_\infty)$ } Damping-in-pitch derivatives, 1/rad
$C_{m_{\theta_E}}$	Effective slope of the pitching-moment curve, 1/rad
Cy_R	Cycles to damp to a given amplitude ratio, R, cycles
d	Reference length (model base diameter), ft
d_s	Diameter of dummy sting, ft
f	Frequency of oscillation, cycles/sec
I	Model moment of inertia about the pivot axis, slug-ft^2
ℓ	Model length, in.
M_θ	Angular restoring-moment parameter, ft-lb/rad
$M_{\dot{\theta}}$	Angular viscous-damping-moment parameter, ft-lb-sec/rad
M_∞	Free-stream nominal Mach number
q	Pitching velocity, rad/sec
q_∞	Free-stream dynamic pressure, lb/ft^2
R	Ratio of amplitude of a damped oscillation after a given number of cycles to the initial amplitude
Re_d	Free-stream Reynolds number based on model base diameter
r_b	Radius of model base, in.
r_n	Radius of model nose, in.
t	Time, sec

V_∞	Free-stream velocity, ft/sec
x_{cg}	Distance from model nose to pivot axis, in.
$\dot{\alpha}$	Time rate of change of angle of attack, rad/sec
θ	Angular displacement, rad or deg
$\dot{\theta}$	Angular velocity, rad/sec
$\ddot{\theta}$	Angular acceleration, rad/sec^2
ω	Angular frequency, rad/sec
$\omega d/2V_\infty$	Reduced frequency parameter, rad

SUBSCRIPT

o	Maximum conditions

SECTION I
INTRODUCTION

Dynamic stability tests were conducted on a 10-deg half-angle cone at Mach number 10 over a Reynolds number range from 0.46×10^6 to 1.84×10^6 based on the model base diameter. The purpose of these tests was to determine the effects of large model oscillation amplitudes (±25 deg) on the dynamic and static stability derivatives, and to investigate the effects of support interference on the derivatives.

The tests, as outlined in Table I, were conducted using a large amplitude (±35 deg), free oscillation gas bearing balance supported by a transverse rod. A 10-in.-base-diam model was used in conjunction with dummy stings to experimentally evaluate effects of the sting support geometry.

SECTION II
APPARATUS

2.1 WIND TUNNEL

The 50-in. Mach 10 tunnel (Gas Dynamic Wind Tunnel, Hypersonic (C)) is a continuous, closed-circuit, variable density wind tunnel. It has a contoured, axisymmetric Mach 10 nozzle and operates at stagnation pressures ranging from 200 to 1800 psia and at stagnation temperatures up to about 1450°F. The model support is capable of being retracted into the test section tank which can be sealed from the airflow for model changes. A description of the tunnel and airflow calibration information may be found in Ref. 1.

2.2 TRANSVERSE ROD BALANCE

The free oscillation balance is a large amplitude (±35 deg) system incorporating a 3-in.-diam cylindrical gas bearing as the balance pivot which is supported by a transverse rod installed in a yoke assembly (Fig. 1). The bearing is capable of supporting a radial load of 300 lb, and a complete calibration of the load carrying capability and damping characteristics of the bearing can be found in Ref. 2.

Photographs of the transverse rod balance are shown in Fig. 2. The variable reluctance angular transducer (Fig. 2, items 3 through 5) provides a continuous time history of model displacement, yet requires no physical connection between the moving and stationary parts of the balance.

The bearing locking system (Fig. 2, items 6 through 9) consists of a gear rack machined on the outer surface of the bearing and an air-actuated piston with a mating set of gear teeth machined on its contact surface. The model may be locked in angular increments of approximately 5 deg.

2.3 MODEL

The model, supplied by the General Electric Company and shown in Figs. 1 and 3, was an axisymmetric conical body of revolution having a 10-deg semi-vertex angle. The model was constructed of stainless steel, and provisions were made to add ballast fore and aft to locate the model center of gravity exactly at the balance pivot axis.

The dummy stings were connected to the center of the aft shield assembly at the rear of the yoke (Fig. 1, item 3). These stings, which were interchangeable, extended up into the base of the model (Fig. 4). A sketch of the model and the dummy stings is shown in Fig. 5.

SECTION III
PROCEDURE

The equations of motion for a free oscillation, one-degree-of-freedom system may be expressed as

$$I\ddot{\theta} - M_{\dot{\theta}}\dot{\theta} - M_{\theta}\theta = 0$$

The method for computing the dimensionless damping-in-pitch derivatives from the free oscillation tests (neglecting tare damping) is indicated by the following expressions:

$$\theta = \theta_0 \left[\exp\left(M_{\dot{\theta}}/2I\right) t\right] \sin \sqrt{-M_{\theta}/I}\; t$$

$$M_{\dot{\theta}} = 2If \; ln \; R/Cy_R$$

$$Cm_q + Cm_{\dot{\alpha}} = M_{\dot{\theta}}\left(\frac{V_\infty}{q_\infty}\right)\left(\frac{2}{Ad^2}\right)$$

Because of the absence of an external restoring moment, the effective slope of the pitching-moment curve may be determined as follows:

$$C_{m_{\theta_E}} = M_\theta / q_\infty A d$$

$$M_\theta = -I \omega^2$$

$$C_{m_{\theta_E}} = -4 (\pi f)^2 I / q_\infty A d$$

The test procedure was to displace the model, while it was in the test section tank, by directing air against the model nose (Fig. 1, item 8) and engaging the lock at the desired release angle. The system was then injected into the airstream and the model released. The resulting oscillatory motion, measured by the angular transducer, was recorded by a direct-writing oscillograph and a high-speed digital converter, which relayed the data by means of magnetic tape to an IBM 7074 computer for data reduction.

SECTION IV
PRECISION OF MEASUREMENTS

The angular transducer was calibrated before and after the tunnel test periods, and check calibrations were made periodically during the tests.

Both the damping-in-pitch derivatives and the static stability derivatives are affected by the uncertainties in determining the model moment of inertia (I) and the angular frequency of oscillation (ω). In addition, the damping derivatives are affected by uncertainties in the amplitude ratio (R). As a result of these sources of possible error, the estimated maximum uncertainty in $C_{m_{\theta_E}}$ is ±2.5 percent, and in $C_{m_q} + C_{m_{\dot{\alpha}}}$ is ±6 percent.

SECTION V
RESULTS AND DISCUSSION

At the present, methods for obtaining high amplitude (±25 deg) dynamic stability data in wind tunnels are limited to the free flight technique and the free oscillation, transverse rod technique. Transverse rod or sting interference effects are not present in free flight testing but large Reynolds numbers are unattainable because of small model size. By using a transverse rod to support the model, data can be obtained at higher Reynolds numbers, but the interference effects of the rod on the aerodynamic derivatives are not known.

Figure 6 shows the variation of the dynamic stability derivatives $(C_{m_q} + C_{m_{\dot{\alpha}}})$ with amplitude of oscillation for a range of Reynolds numbers. The present data are compared with free oscillation data obtained with a sting-supported model (Ref. 3). Although the majority of the Reynolds numbers are not exactly matched in the data comparison, it is evident that as the Reynolds number is increased there is better agreement between data obtained with the transverse rod and the sting-supported models.

As shown in Ref. 4, boundary-layer transition occurs at the model base on a 10-deg cone at Mach number 10 (Tunnel C) at a Reynolds number of about 1.4×10^6 based on model base diameter. Data obtained during these tests (Ref. 4) also show that at a Reynolds number of 1.83×10^6 the beginning of boundary-layer transition occurs at about 70 percent of the model surface length for a sting-supported model. The comparison between the data obtained with the rod-supported model and the sting-supported model is best at the higher Reynolds numbers where at $\theta = 0$ the boundary layer of the sting-supported model is primarily turbulent behind the point of rod contact. The flow field theory (Ref. 5) shows fair agreement with the dynamic stability data obtained with a sting-supported model at all Reynolds numbers (Fig. 6).

The variations of the static stability derivative $(C_{m_{\theta_E}})$ with amplitude of oscillation are shown in Fig. 7 and are compared with data obtained with a sting-supported model (Ref. 3). Data obtained with a transverse rod model support are at a higher level than the sting-supported model data at all Reynolds numbers, and, as was the case with the dynamic derivatives, the agreement is better at the maximum Reynolds number. The conical flow theory shows favorable agreement with the data from the sting-supported model and implies that the rod support interference does affect the cone static stability at all Reynolds numbers investigated. For all Reynolds numbers, increasing amplitude of oscillation showed no large variations in the effective slope of the pitching-moment curve.

Figure 8 shows the variation of the dynamic and static stability derivatives with Reynolds number and also shows a comparison with data from a sting-supported model (Ref. 3) and with free flight range data (Ref. 6). The data obtained from the range confirm that the damping-in-pitch derivatives at the lower Reynolds numbers are affected by rod interference. The free flight static stability data obtained in the range confirm the level of the static stability data obtained with a sting-supported model and show that the static stability data obtained with the transverse rod support system are affected by rod interference at all Reynolds numbers.

Figure 9 shows the effect of sting support geometry on the dynamic and static stability derivatives with varying amplitude of oscillation and with increasing sting diameter ratio. An effect of sting support diameter is indicated in Fig. 9a where damping data obtained with the dummy sting configuration (Configuration 1-C, $d_s/d = 0.18$) agree well with Configuration 1 ($d_s/d = 0$) for the smaller angles of oscillation ($\theta \leq \pm 4.5$ deg), but have a higher level of damping for angles of oscillation greater than ±4.5 deg. Decreasing the effective sting length (Configuration 1-D) produced a higher level of model damping at amplitudes of oscillation less than about ±6 deg as compared to Configuration 1-C (Fig. 9a). The slopes of the pitching-moment curves were essentially unaffected by the dummy sting geometry variations. It should be noted that the true effect of sting support geometry on the dynamic and static derivatives could have been masked by the interference produced by the transverse rod.

SECTION VI
CONCLUDING REMARKS

Dynamic stability tests were conducted to determine the effects of large amplitudes of oscillation and support interference on the dynamic and static stability characteristics of a 10-deg cone.

Data were obtained at Mach number 10 at Reynolds numbers ranging from 0.46×10^6 to 1.84×10^6. Conclusions based on the results presented in this report are given below:

1. Transverse rod interference decreased the level of the damping-in-pitch derivatives at the lower angles of oscillation for all Reynolds numbers except 1.83×10^6 where good agreement was obtained between results from the rod-supported and sting-supported models. However, the validity of the transverse rod data at amplitudes of oscillation greater than those obtainable with a sting-supported model is still unknown.

2. Rod interference increased the level of the static stability derivatives.

3. Sting support geometry effects were inconclusive since rod interference was present.

In light of the above conclusions, it is evident that tests using the large amplitude, transverse rod technique should be supplemented by both the sting-supported model tests and wind tunnel or range free flight tests.

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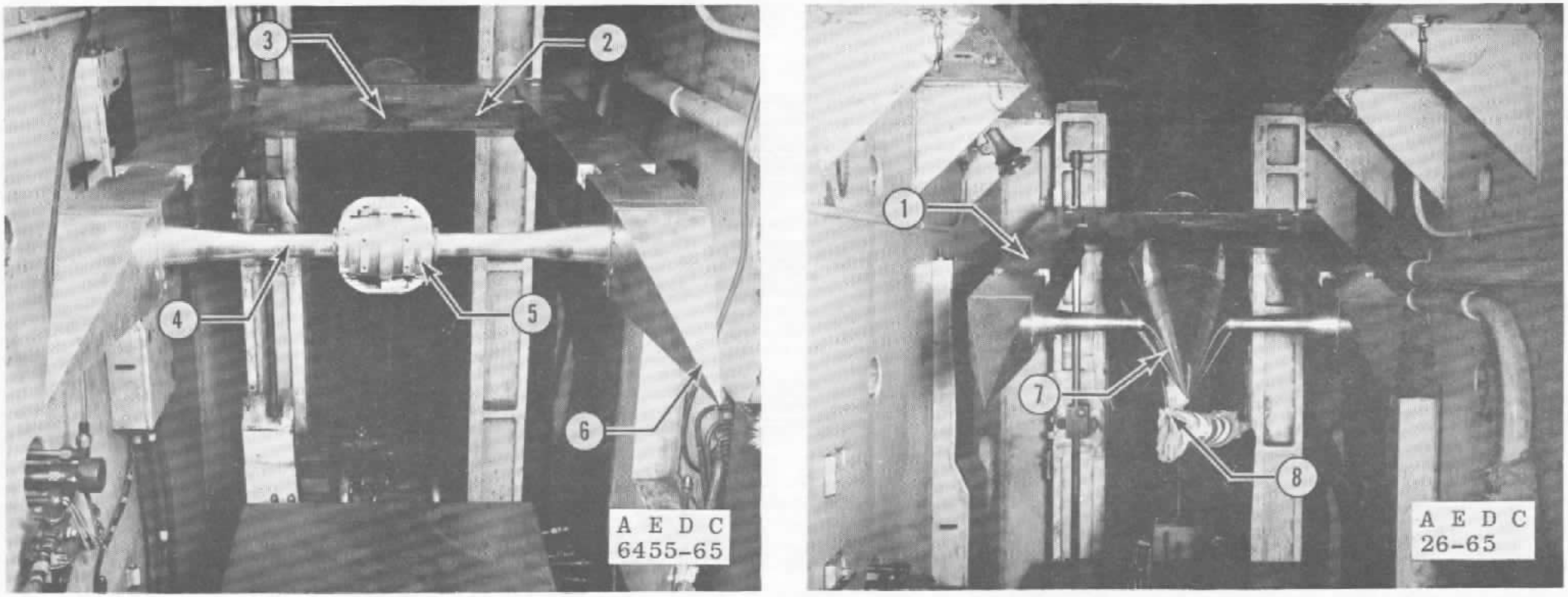
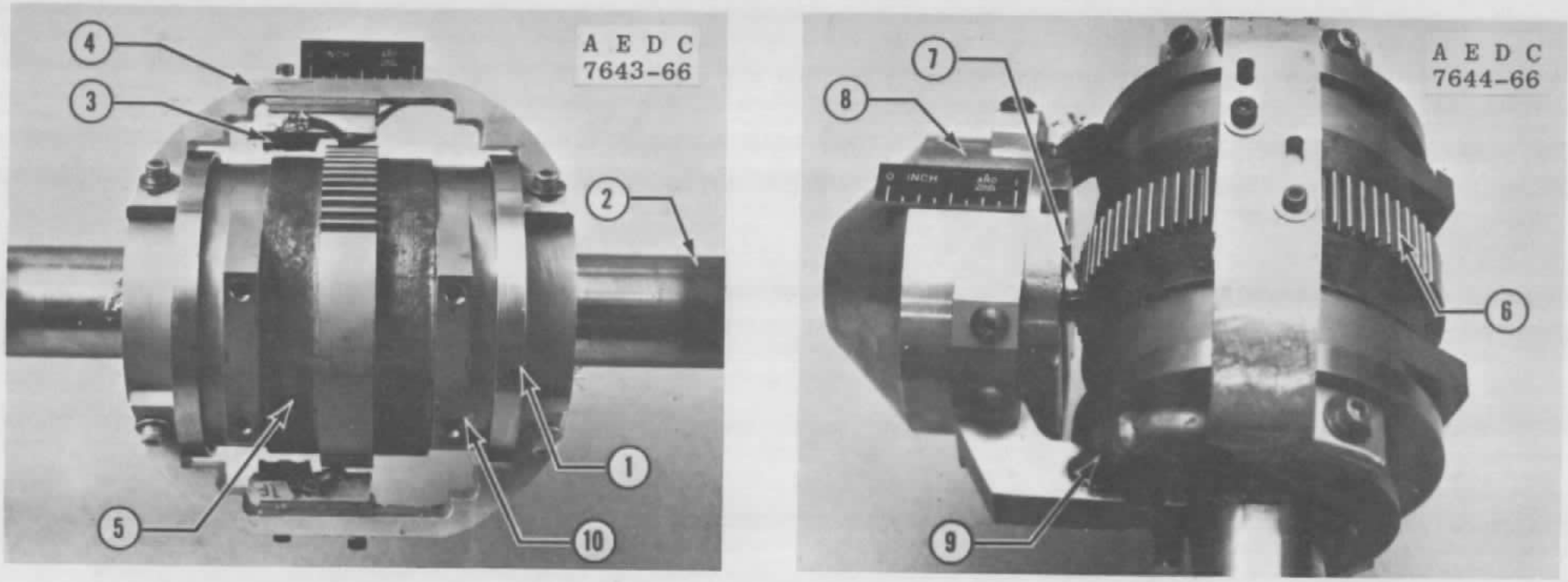


Item No.	Description	Item No.	Description
1	Yoke Assembly	5	Gas Bearing
2	Aft Shield Assembly	6	Fore Shield Assembly
3	Point of Contact for Dummy Sting	7	Model
4	Transverse Rod	8	Model Displacement Air Line

Fig. 1 Photographs of the Transverse Rod and Yoke System Installed in Test Section Tank



Item No.	Description
1	Gas Bearing
2	Transverse Rod
3	"E" Core
4	"E" Core Mounting Bracket
5	Eccentric
6	Gear Rack
7	Air Actuated Piston
8	Lock Housing for Air Piston
9	Lock Actuating Air Line
10	Model Mounting Pad

Fig. 2 Photographs of the Free Oscillation (±35 deg) Transverse Rod Balance

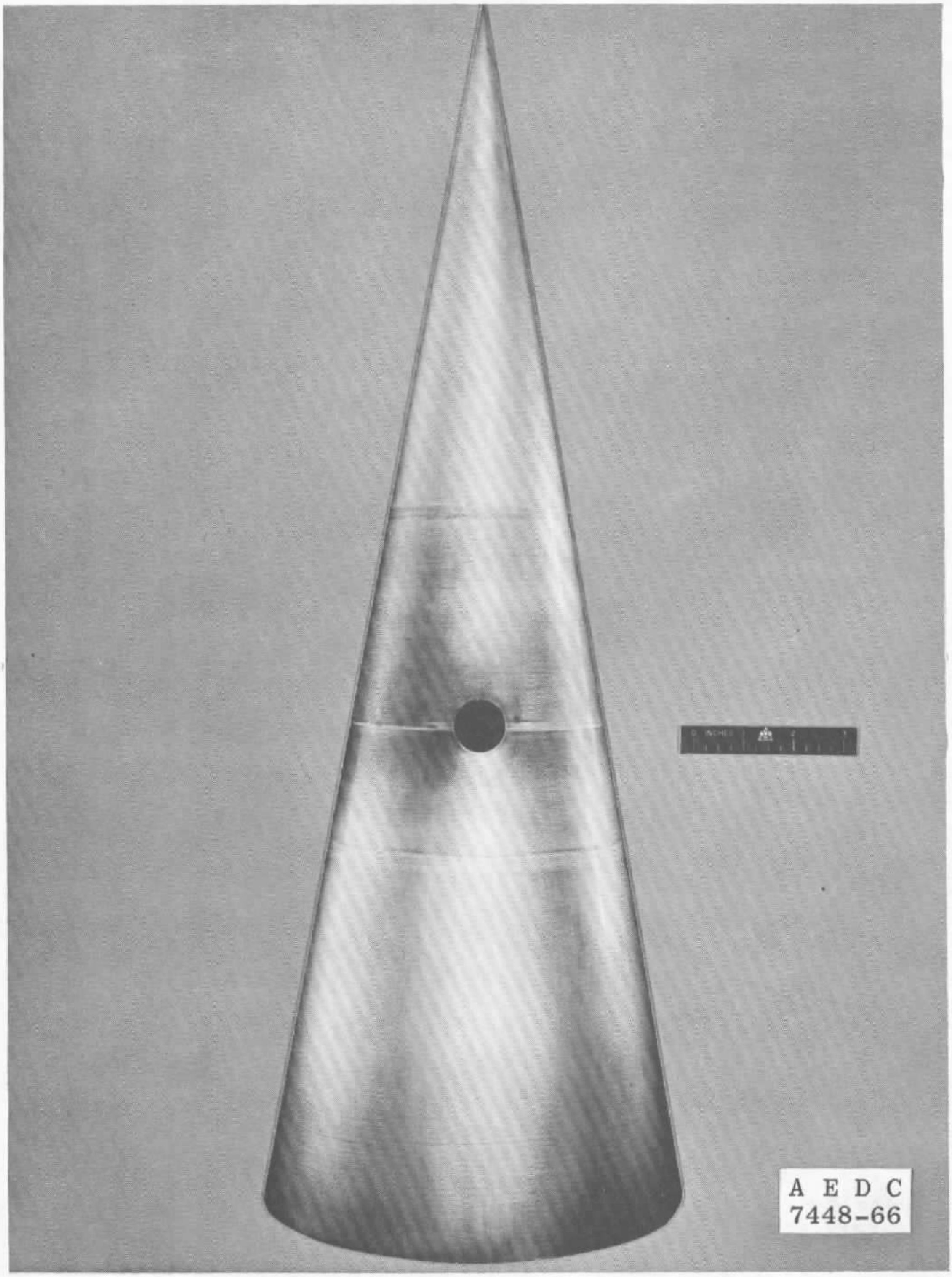


Fig. 3 Photograph of the Model

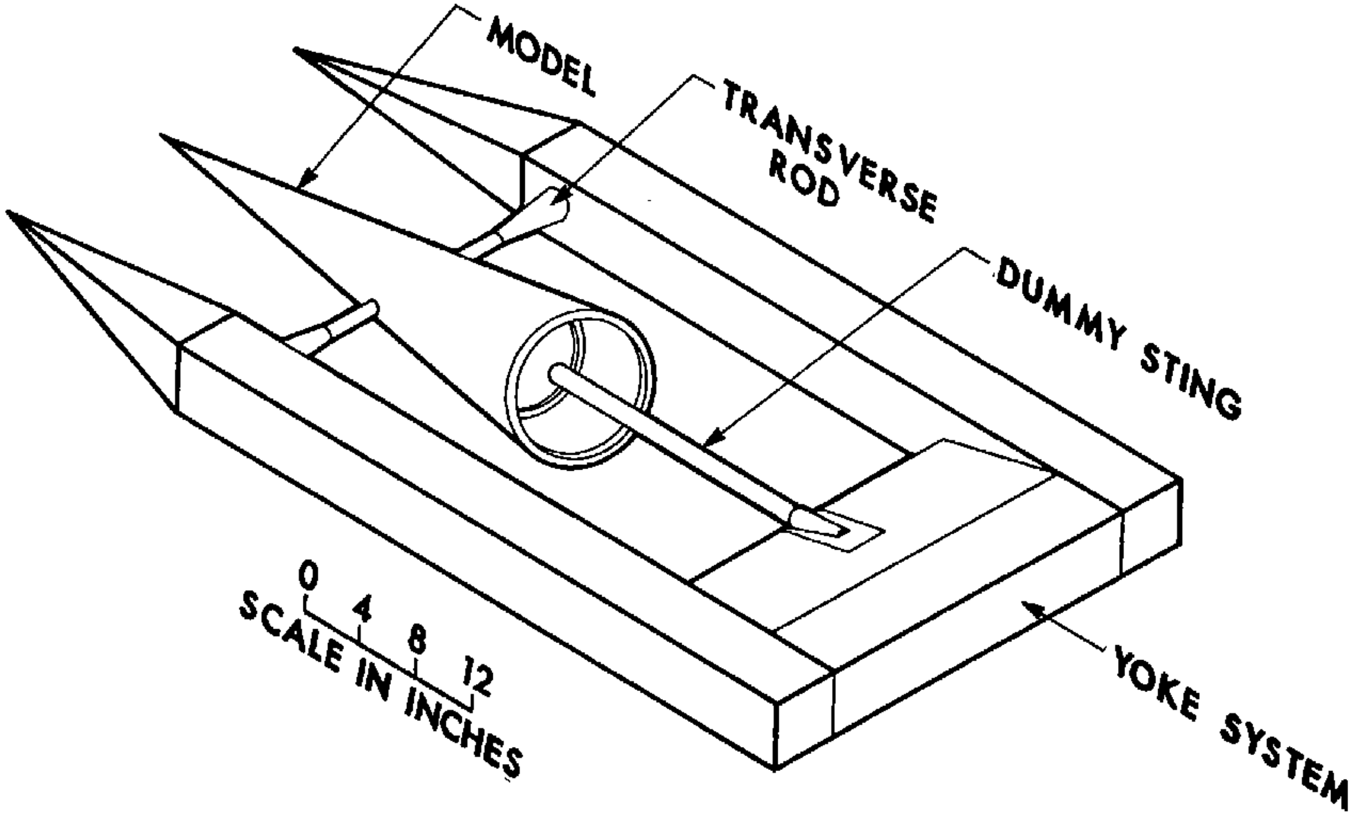
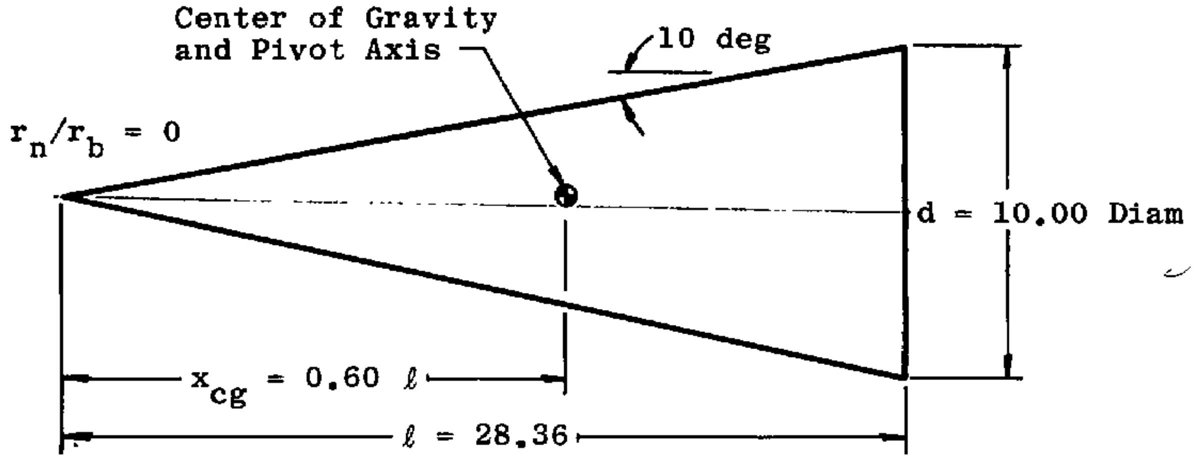
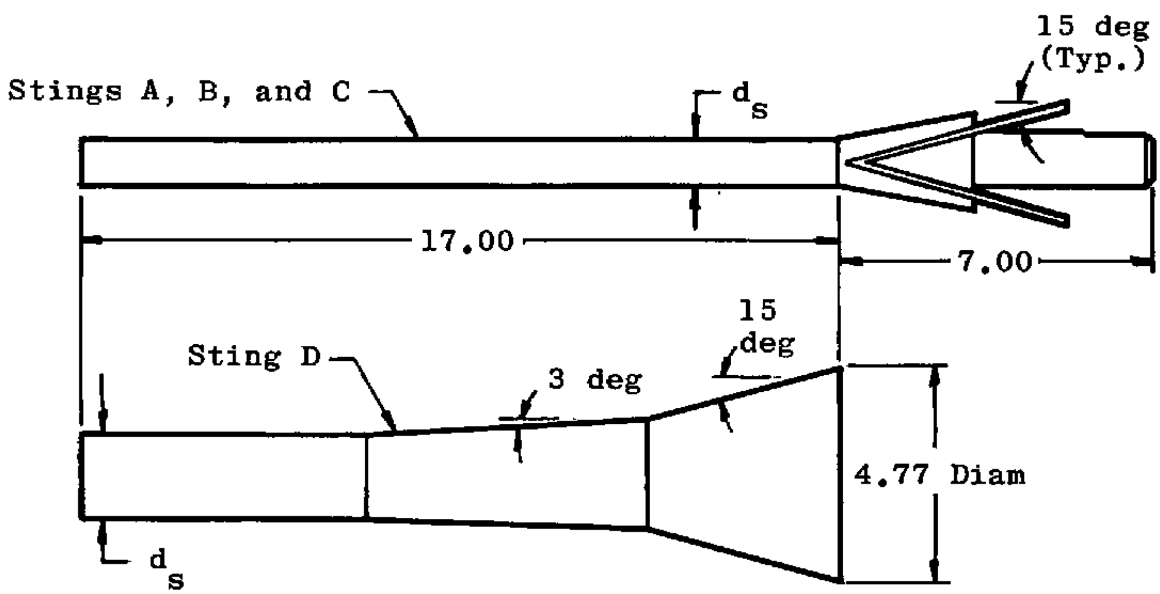


Fig. 4 Sketch of Model, Transverse Rod, and Yoke System



a. Model Geometry



Sting	d_s
A	0.60
B	1.20
C	1.80
D	1.80

Note: All Dimensions in Inches
Configurations such as 1-A Indicate Model (1) and Sting (A, B, C, or D) Combination

b. Dummy Sting Geometry

Fig. 5 Model and Dummy Sting Geometry

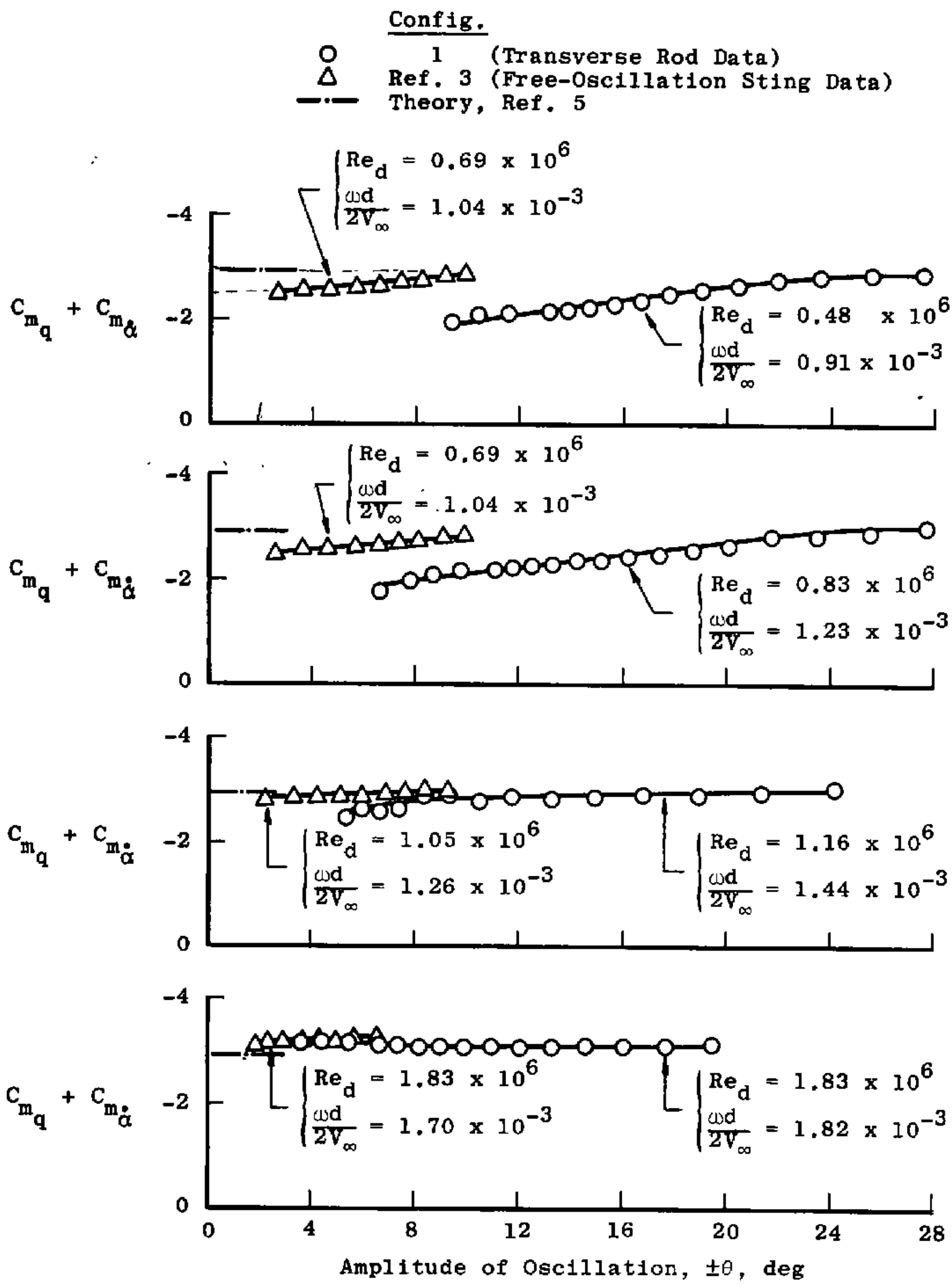


Fig. 6 Dynamic Stability Derivatives versus Amplitude of Oscillation

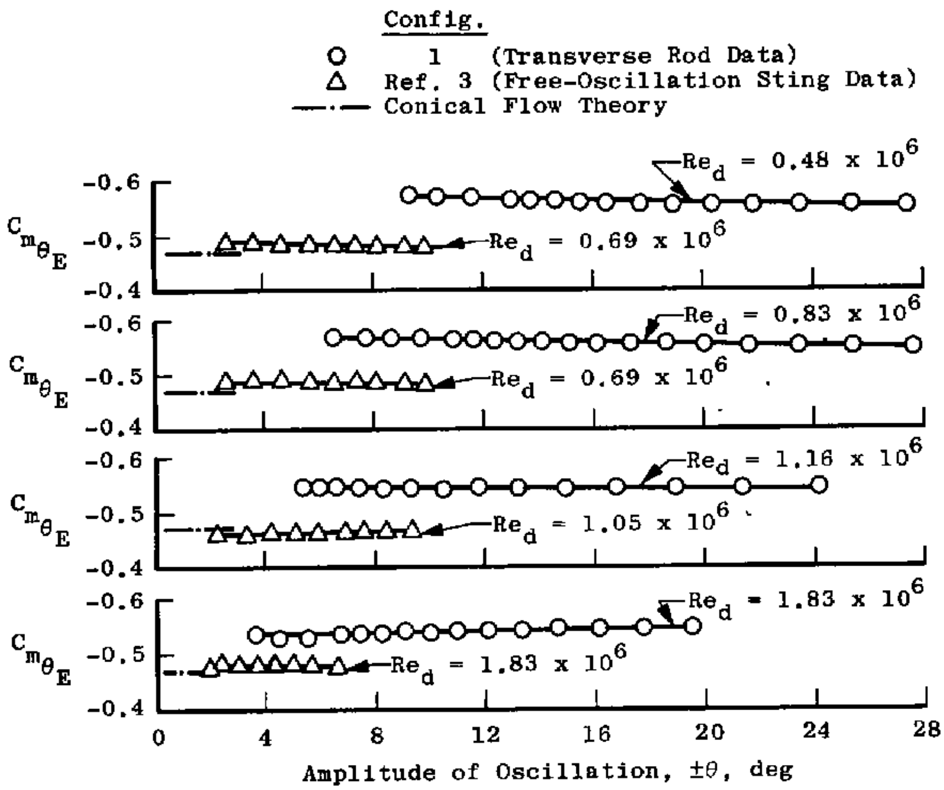


Fig. 7 Static Stability Derivatives versus Amplitude of Oscillation

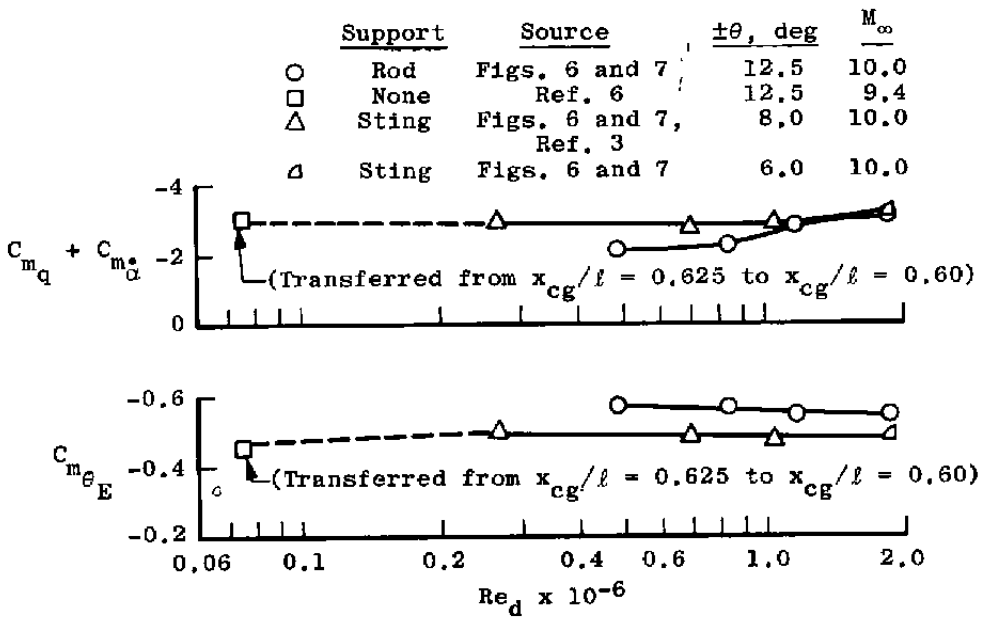
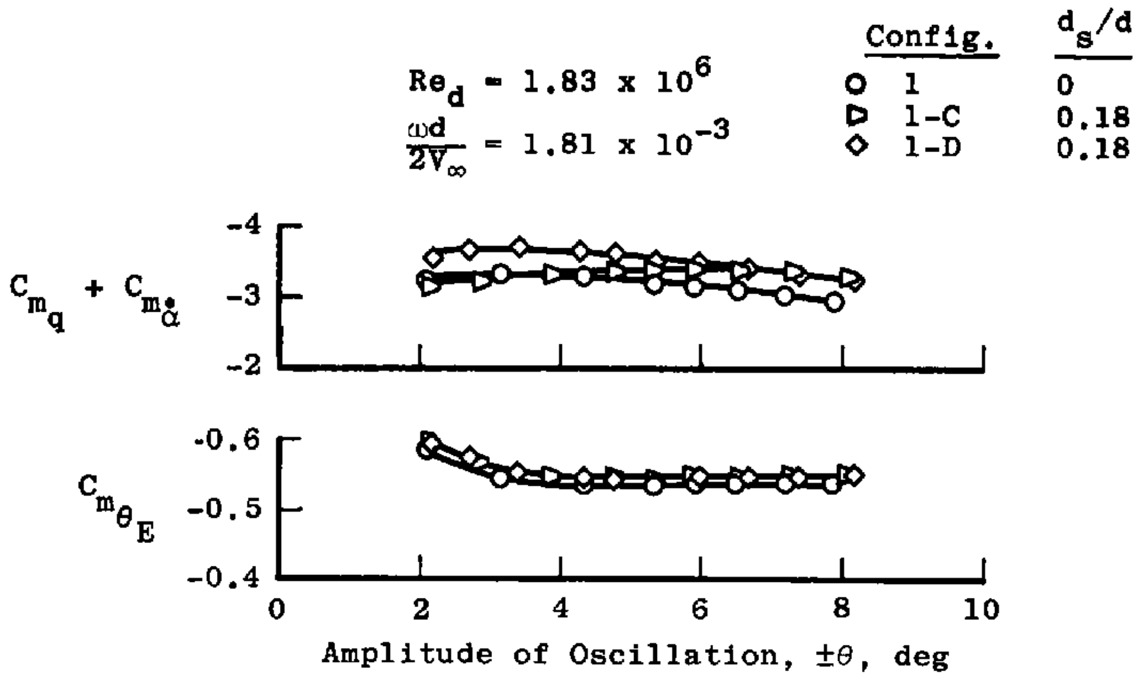
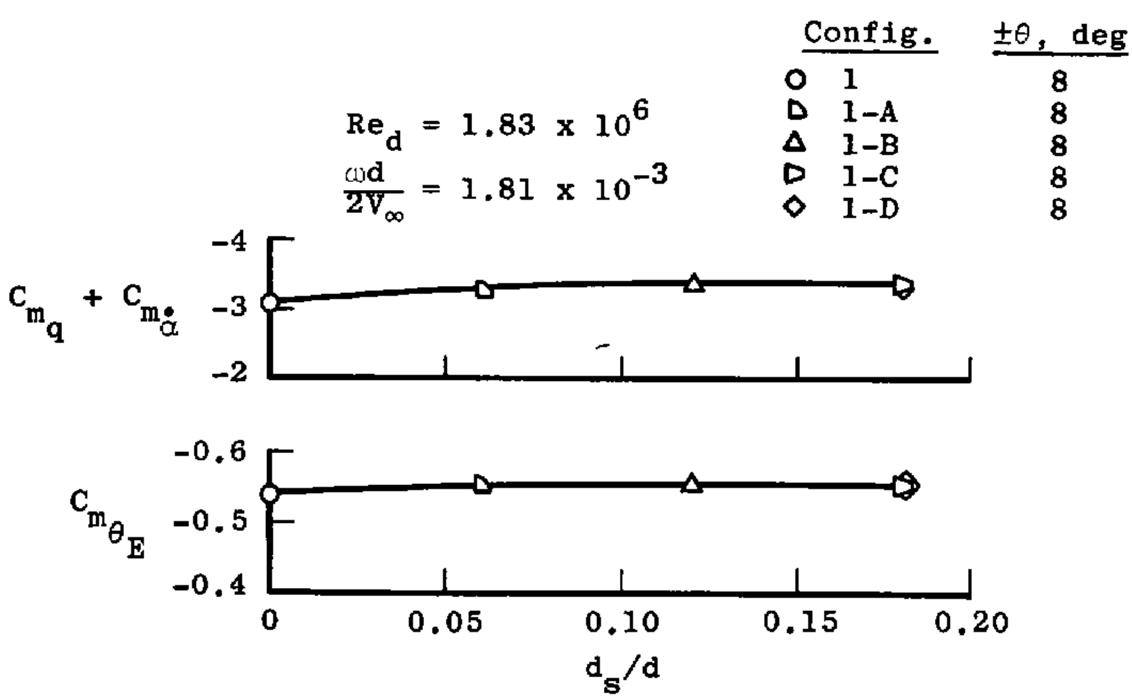


Fig. 8 Dynamic and Static Stability Derivatives versus Reynolds Numbers



a. Dynamic and Static Stability Derivatives versus Amplitude of Oscillation



b. Dynamic and Static Stability Derivatives versus Sting Diameter Ratio

Fig. 9 Effect of Sting Support Geometry

TABLE I
SUMMARY OF TEST CONDITIONS

Configuration	$Re_d \times 10^{-6}$	Release Angle, deg	$\pm\theta$, deg
1	0.47, 0.83, 1.15, 1.51	5	2.1-4.6
1	0.48, 0.83, 1.18, 1.48, 1.83	8-13	1.3-12.8
1	0.48,* 0.83,* 1.16,* 1.83*	22-33	2.8-31.9
1-A	0.46, 0.83, 1.18, 1.48, 1.81	6	1.2-5.3
1-A	0.47, 0.83, 1.16, 1.49, 1.83*	8-10	1.1-9.3
1-B	0.47, 0.83, 1.16, 1.51, 1.84	6	1.4-5.3
1-B	0.48, 0.83, 1.16, 1.49, 1.83*	8-10	2.0-9.2
1-C	0.48, 0.83, 1.17, 1.50	6	2.0-5.3
1-C	0.46, 0.83, 1.16, 1.49, 1.83*	8-10	2.0-9.2
1-D	0.47, 0.83, 1.06, 1.50, 1.83	6	2.0-5.3
1-D	0.47, 0.83, 1.07, 1.51, 1.83*	8-10	2.0-9.2

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