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A TWO-DEGREE-OF-FREEDOM FLUTTER MOUNT SYSTEM WITH LOW DAMPING FOR TESTING RIGID WINGS AT DIFFERENT ANGLES OF ATTACK

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SUMMARY

A wind-tunnel model mount system for conducting flutter research using a rigid wing has been developed. The wing is attached to a splitter plate so that the two move as one rigid body. The splitter plate is supported away from the tunnel wall by a system of rods with fixed-fixed end conditions. The rods flex in such a way that only pitch and plunge oscillations are permitted. At the tunnel wall the rods are attached to a remotely controlled turntable so that angle of attack can be varied. Wind-tunnel data obtained by using the mount system are presented for a supercritical and a conventional airfoil. Both classical flutter and stall flutter data are presented.

INTRODUCTION

Flutter is a self-excited oscillation in an airstream of an elastic body, such as a venetian blind or the wing and tail surfaces of an airplane, which occurs when aerodynamic damping becomes negative and greater in magnitude than the positive damping inherent in the structure. References 1 through 4 are textbooks which treat the subject of flutter comprehensively. To insure that new aircraft are safe, it is necessary to know that they will not encounter flutter within their operating envelope of altitude and velocity.

Because flutter is a very complex phenomena involving an intricate interaction of structural stiffness and inertia forces with aerodynamic forces produced by motion of the structure itself, a large portion of flutter research is conducted experimentally. Although analytical methods are available, they are not developed to the extent that they give sufficiently accurate results in regions where nonlinear effects are important, such as at transonic speeds and at angles of attack. This paper describes a new mount system concept for wind-tunnel models that can be used to study the effects of angle of attack on flutter.

Figure 1 shows a streamwise cross section of a typical airfoil. The steady state angle of attack α is that angle at which the chordline of the airfoil is oriented relative to the direction of flow. Pitch motion of the airfoil is defined as rotation about any axis perpendicular to the plane of figure 1. In this paper, plunge motion is defined as translation in a direction which is parallel to the plane of figure 1 and perpendicular to the chordline of the airfoil.

To conduct basic wind-tunnel flutter studies, it is desirable to use models which are as simple as practical yet still represent the important flutter parameters. A model mount system which provides for pitching and plunging degrees of freedom would meet this requirement for many research studies. This is because the flutter characteristics of a rigid wing with pitching and plunging degrees of freedom are qualitatively very similar to the flutter characteristics of more complex, three dimensional, flexible wings with bending and torsion structural modes. The model mount system must be strong enough to carry large steady state and dynamic loads and must provide linear elastic constraints so that the model will oscillate sinusoidally in pitch and plunge if it is excited. The oscillations are functions of the elastic restraints, the mass properties of the model and any structure attached to it, and the forces on the model. Previously, mount systems such as those described in references 5 through 7, have employed bearings to support those parts of the device that move. These bearings inherently introduced damping which could change as the loads on the model changed. A very important characteristic of the mount system described herein is that the very small amount of damping which it introduces remains constant as the loads on the model change. This means that aerodynamic damping is almost all of the damping which influences motion of the model, and it is therefore possible to accurately study how the aerodynamic damping varies as flow over the model is changed.

Using this new concept, the model to be tested is attached to a splitter plate so that the two move as one rigid body. The splitter plate is supported out from the tunnel wall by a system of rods with fixed-fixed end conditions. The rods flex in such a way that only pitch and plunge oscillations are permitted. At the tunnel wall the rods are attached to a remotely controlled turntable so that α can be varied.

This paper will discuss the development of a prototype of the mount system and the use of the prototype to obtain wind-tunnel data in the Langley Transonic Dynamics Tunnel (TDT).

SYMBOLS

D rod diameter, ft.

E Young's modulus, lbf/ft^2

f_p fundamental plunge frequency, Hz

f_θ fundamental pitch frequency, Hz

G shear modulus, lbf/ft^2

I area moment of inertia, ft^4

I_M mass moment of inertia in pitch, $slug \cdot ft^2$

J polar moment of inertia, of a circular cross section, ft^4

K_p plunge spring constant, lbf/ft

K_θ pitch spring constant, $ft \cdot lbf/RAD$

L rod length, ft

M mass, slugs

P	concentrated load, lbf
q	dynamic pressure, lbf/ft^2
R	radius of hole pattern for circular rods, ft
T	concentrated torque, ft·lbf
V	flow velocity, ft/sec
Y	linear deflection, ft
α	angle of attack, degrees
θ	angular deflection, radians
ρ	flow density, $slugs/ft^3$

MOUNT SYSTEM DEVELOPMENT

Spring Constants

Before describing the mount system, it is desirable to review the stiffness theory which is used to calculated the pitch and plunge spring constants.

First, consider the bending deflection of a beam of length L such as shown in figure 2 which has a concentrated load P at end B. The beam is fixed at end A and constrained at end B so that the deflection slope at end B remains zero as end B translates. The effective spring constant at end B as derived using simple beam theory is:

$$\frac{P}{Y} = \frac{12\ EI}{L^3} \tag{1}$$

Second, consider the beam as a rod which has a concentrated torque T applied at end B. If the beam has a circular cross section the effective torsion spring constant at end B is:

$$\frac{T}{\theta} = \frac{GJ}{L} \tag{2}$$

For a beam with a circular cross section, the area moment of inertia I and the polar moment of inertia J are defined:

$$I = \frac{\pi D^4}{64}, \quad J = \frac{\pi D^4}{32} \tag{3}$$

Using equations (1) through (3), the following relations can be derived:

$$\frac{P}{Y} = \frac{12E\left(\frac{\pi D^4}{64}\right)}{L^3} = \frac{.589ED^4}{L^3}, \tag{4}$$

and

$$\frac{T}{\theta} = \frac{G\left(\frac{\pi D^4}{32}\right)}{L} = .0982\,\frac{GD^4}{L} \tag{5}$$

Design Concepts

Schematic drawings of the mount system are shown in figure 3. The rigid wing is attached to a splitter plate so that the two move together as one rigid mass. The splitter plate is attached to a turntable whose face is flush with the wind-tunnel sidewall as shown in figure 3a. The angle of attack of the wing can be changed by rotating the turntable.

The most important feature of the apparatus is the method used to attach the splitter plate to the turntable. Four circular rods are screwed into both the turntable and splitter plate so that each end of each rod is in a fixed condition. The four rods are equally spaced around a circle of radius R as shown in figure 3b. The rods have the same diameter D. Because the fixed ends of the rods are prevented from moving longitudinally, no roll or yaw deflection of the splitter plate occurs; in other words, the plane of the splitter plate remains parallel to the plane of the tunnel wall. Roll and yaw moments are carried by axial compression and tension loads on the rods. Part of the design process is to insure that no roll or yaw deflections of the splitter plate occur because of the axial deflections of the rods.

The plunge spring constant provided by the four rods is simply four times the bending spring constant provided by one rod.

$$K_P = 4\left(\frac{P}{Y}\right) \tag{6}$$

The rods provide pitch stiffness in two ways. First, as the splitter plate rotates through an angle θ, each rod must have a twist deflection equal to θ. Second, each rod must have a bending deflection equal to $R\theta$. The resulting spring constant is given by the following equation:

$$K_\theta = 4\left[\frac{T}{\theta} + \left(\frac{P}{Y}\right)R^2\right] \tag{7}$$

Another fixed-fixed beam, with a thin rectangular cross section, is attached to the turntable and splitter plate to make the stiffness of the splitter plate restraint perpendicular to the direction of plunge much greater than the stiffness in the plunge direction. If it were not for this beam, called a drag strut, the translation stiffness of the system would be the same in any direction in the plane of the splitter plate. The contribution of the drag strut to the pitch and plunge stiffnesses of the mount system is much less than the contribution of the four circular rods. A windscreen, shown in figure 3b, is attached to the turntable and extended out almost to the splitter plate. This windscreen, which is not involved in the system dynamics, prevents flow over the drag strut which might contribute aerodynamic damping. In addition, if plunge oscillations of the splitter plate become excessive, the drag strut begins to strike the windscreen; thereby limiting the oscillation amplitude.

Prototype Demonstration Mount System

Photographs of the mount system with a wing mounted thereon are shown in figures 4 and 5. The circular rods are made of 17-4 stainless steel heat treated to obtain an ultimate yield stress of about 160,000 psi; L is 3.10 feet, R is .625 feet, and D is .052 feet. The rods are screwed into both the turntable plate and the splitter plate to a depth of 1 inch. To facilitate assembly each rod has left hand threads on one end and right hand threads on the other. At both ends of each rod, a standard nut has been pulled tight against the plate to help obtain fixed end conditions.

The drag strut, which has a rectangular cross section (.25 x 3 inches), is made of carbon steel. The windscreen is also made of carbon steel.

The splitter plate consists of a one-inch thick, 24-inch diameter steel plate and a one-half-inch-thick, 42-inch-diameter plywood plate which is bolted to the outer surface of the steel plate. The center of gravity of the splitter plate is at its geometric center.

The center of the hole pattern for the circular rods is at the center of the splitter plate. The drag strut is attached to the center of the splitter plate.

The measured spring constants of the mount system are:

$$K_P = 2623 \text{ lbf/ft}; \; K_\theta = 3020 \text{ ft lbf/Rad}$$

These values are slightly greater than values obtained from equations (6) and (7) which do not include the contribution of the drag strut.

The total mass and inertia properties of the splitter plate and airfoil are: $M = 5.49$ slugs; $I_M = 2.83$ slug ft^2.

The measured pitch and plunge natural frequencies of the apparatus are 5.20 Hz and 3.48 Hz. These frequencies can also be calculated from the following relationships.

$$f_\theta = \frac{1}{2\pi}\sqrt{\frac{K_\theta}{I_M}} = 5.20 \text{ Hz}$$

$$f_p = \frac{1}{2\pi}\sqrt{\frac{K_p}{M}} = 3.48 \text{ Hz}$$

These measured frequencies are in good agreement with calculated frequencies obtained with calculated mass and inertia properties.

The apparatus was designed so that flutter data could be obtained within the operating boundary of the Langley Transonic Dynamics Tunnel. Having the pitch frequency higher than the plunge frequency is desirable from a flutter research point of view. For both the pitch and plunge modes the measured damping coefficient in still air is about .001, which is very small.

WIND-TUNNEL DEMONSTRATION

A wind-tunnel test has been conducted in the Langley Transonic Dynamics Tunnel (TDT) to demonstrate the prototype mount system.

Apparatus

Airfoils.- Data are presented in this paper for two wings with two different airfoils. Both wings have rectangular planforms with a chord of 1 foot and a semispan of 3.0 feet--i.e., the total planform area of each wing is 3.0 square feet. The construction technique employed was to cover an aluminum plate with balsa and then sand the balsa down to the desired airfoil shape. One wind had a symmetric NACA 64A010 airfoil; the other had a symmetric 10%-thick supercritical airfoil. Both wings were attached to the mount with their midchord positions one-half inch forward of the center of the splitter plate. The mass properties of the two wings are essentially identical.

Wind Tunnel.- The TDT is a continuous-flow, single-return tunnel with a 16-ft square test section (with cropped corners) having slots in all four walls (ref. 8). The flow is generated by a motor-driven fan. The tunnel is equipped to use either air or Freon[1] as a test medium at pressures which vary from near vacuum to slightly above atmospheric. Mach number and dynamic pressure can be varied simultaneously or independently. Mach number is the ratio of the flow velocity to the velocity of sound in the test medium. Dynamic pressure is a measure of the kinetic energy in the airstream and can be calculated using the following equation.

$$q = \frac{1}{2}\rho V^2$$

Instrumentation.- The true angle of attack of the airfoil was obtained from an angle of attack accelerometer mounted on the splitter plate. The true angle of attack differed from a value obtained from the turntable position indicator because steady state aerodynamic forces on the airfoil caused the mount system to deflect in pitch.

Oscillatory motion of the airfoil-splitter plate body was sensed by accelerometers mounted on the splitter plate and by strain-gages mounted on the

[1]Freon: Registered trademark of E. I. du Pont de Nemours & Co., Inc.

drag strut. The motion was monitored and recorded on a strip chart. Time histories of the motion were recorded and analyzed to calculate aerodynamic damping using a digital computer which is part of the TDT Data Acquisition System. The Data Acquisition System is described in reference 9.

Results and Discussion

In order to demonstrate the use of the mount system, both classical flutter and stall flutter were studied.

Classical flutter - This type of flutter occurs at low angles of attack, and is caused by the aerodynamic coupling of two or more structural modes. The frequency of the flutter oscillation is often between the frequencies of the structural modes involved in the flutter.

The classical flutter boundaries for two airfoils are presented in figure 6. For these data the true angle of attack was always less than one degree. Each of the measured flutter points was obtained by slowly increasing Mach number and dynamic pressure until sustained sinusoidal flutter was observed. The flutter frequency was usually between 4.5 and 5.0 Hz. The flutter mode was a coupled oscillation involving the pitch and plunge structural modes. The pitch mode appeared to be dominant. It can be seen that the transonic dip in the classical flutter boundary of the supercritical airfoil is more pronounced than for the conventional airfoil. This is consistent with previous data for supercritical wings such as those presented in reference 10.

Stall flutter.- This type of flutter, which is caused by periodic separation and reattaching of flow over some portion of the airfoil, can occur when the angle of attack is near the value for which steady state stall occurs. Stall flutter usually involves only one structural mode. For unswept airfoils, stall flutter usually occurs in a structural mode which is characterized by pitching motion. It also may be possible that a phenomenon similar to stall flutter can occur at relatively low angles of attack in the transonic region because of the periodic movement of shock waves on the airfoil.

Measured stall flutter data for the conventional airfoil at subsonic Mach numbers in air are shown in figure 7. Each data point was obtained by first establishing the tunnel flow conditions and then increasing the angle of attack until flutter occurred. For small values of dynamic pressure, less than 40 psf, flutter did not occur until the angle of attack was above 8 degrees. Over an intermediate range of dynamic pressure, from about 40 to 90 psf, the critical angle of attack was about 8 degrees. As the dynamic pressure was increased further, the critical angle of attack rapidly decreased until the classical flutter boundary was reached. The classical flutter boundary in air was slightly lower than the Freon boundary which is shown in figure 6. The data shown in figure 7 are qualitatively very similar to results presented in references 5 and 11.

Measured stall flutter data for the supercritical airfoil at .75 Mach number in air are shown in figure 8. For values of dynamic pressure below about 100 psf the critical angle of attack was about 7°. As the classical flutter boundary was approached, the critical angle of attack decreased rapidly as it had for the conventional airfoil.

For both airfoils, the stall flutter frequency was usually between 4.9 and 5.1 Hz. The motion appeared to consist entirely of pitch oscillations.

CONCLUDING REMARKS

The development of a relatively simple wind-tunnel mount system concept for conducting flutter research studies has been described. The properties of the prototype mount system agreed well with those predicted analytically. It has been shown that both classical and stall flutter data can be obtained. The results obtained are consistent with results from other studies indicating that good quality flutter research data can be obtained by using this mount system.

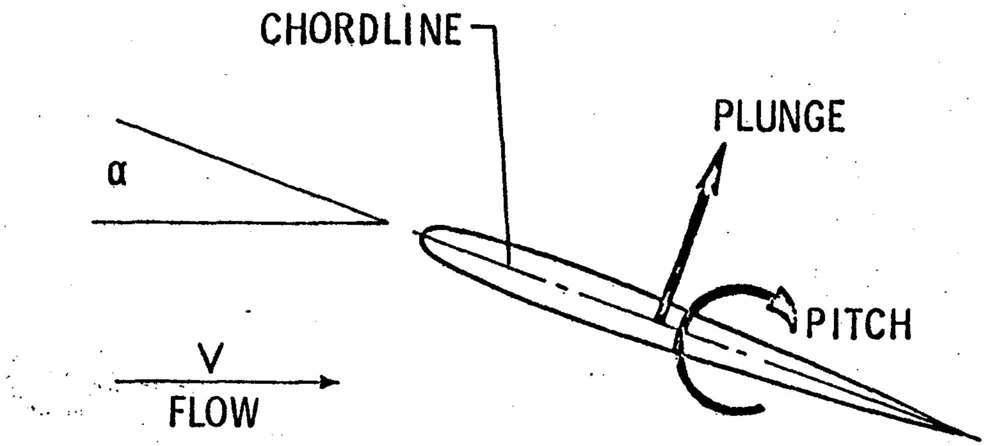


Figure 1.- The pitch and plunge degrees of freedom of an airfoil.

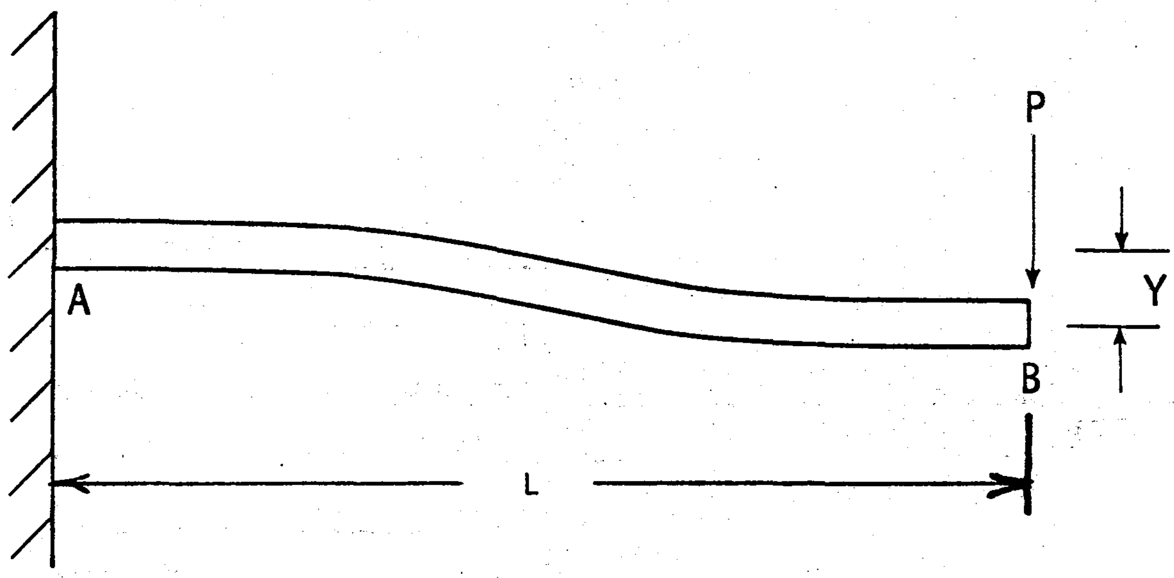
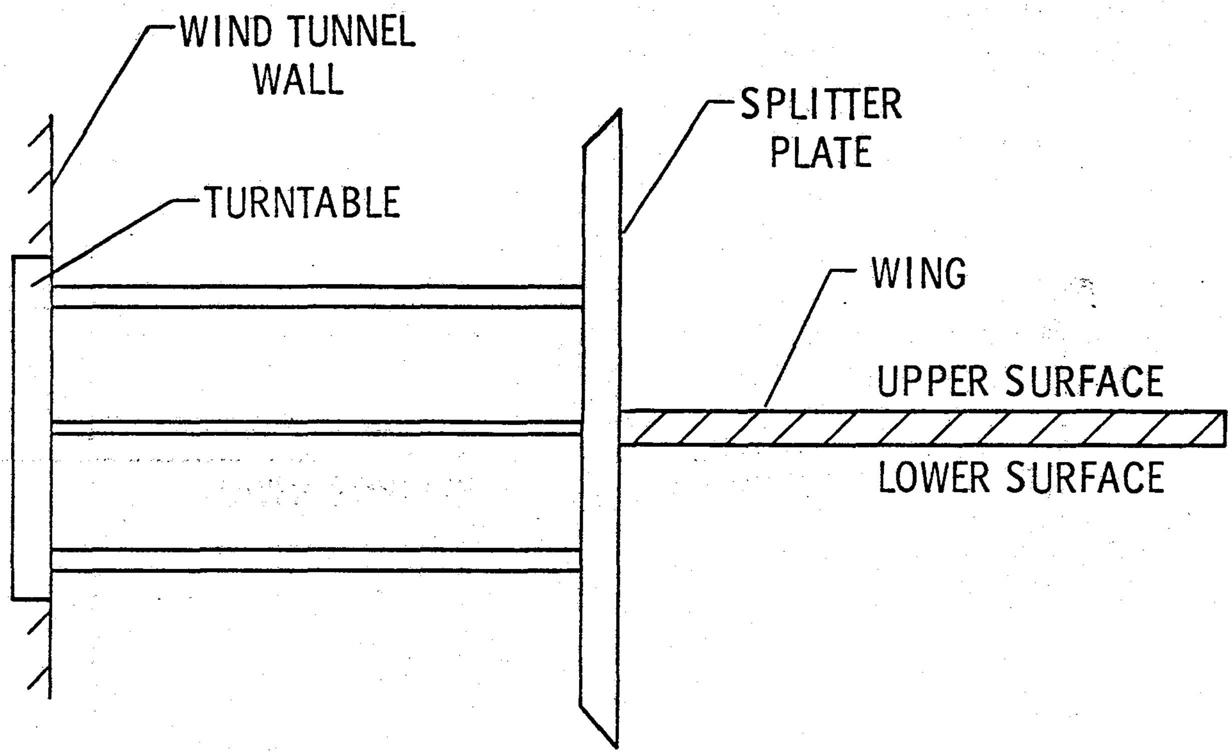
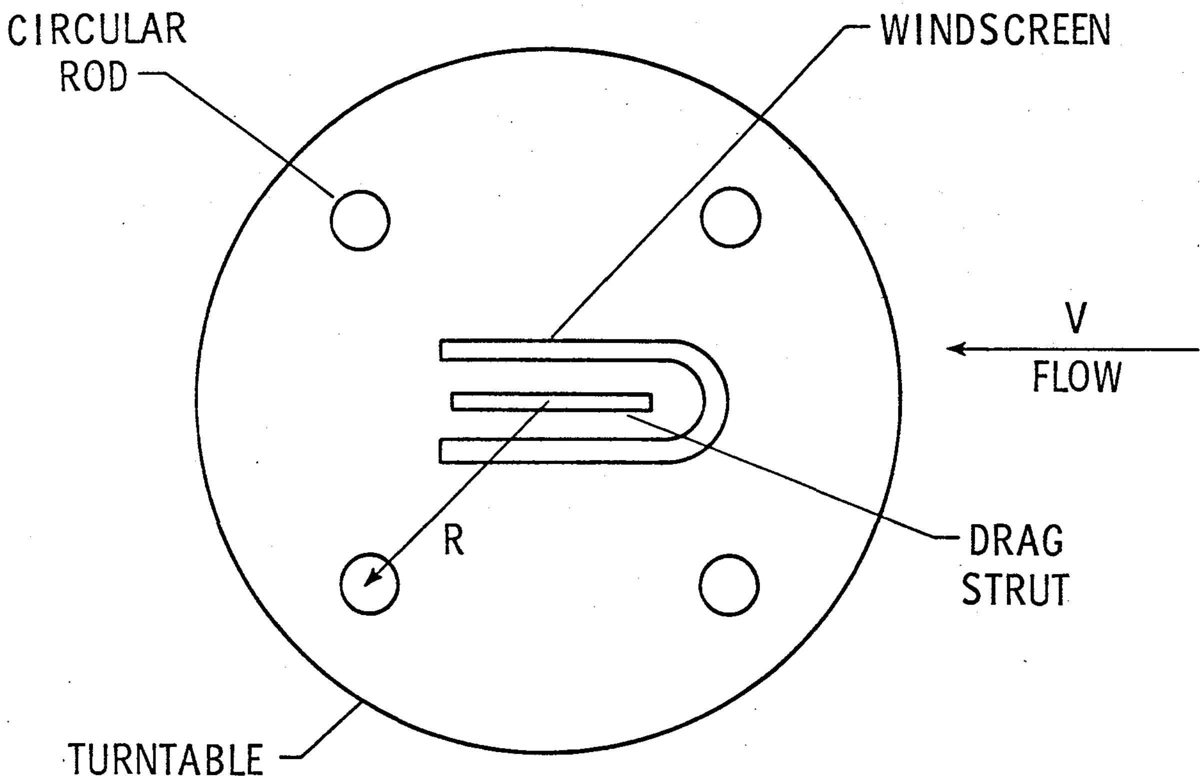


Figure 2.- Schematic drawing of beam bending deflection.



(a) Horizontal view looking upstream (windscreen not shown)

Figure 3.- Schematic drawings of mount system and wing.



(b) Horizontal view looking perpendicular to the face of the turntable

Figure 3.- Concluded.

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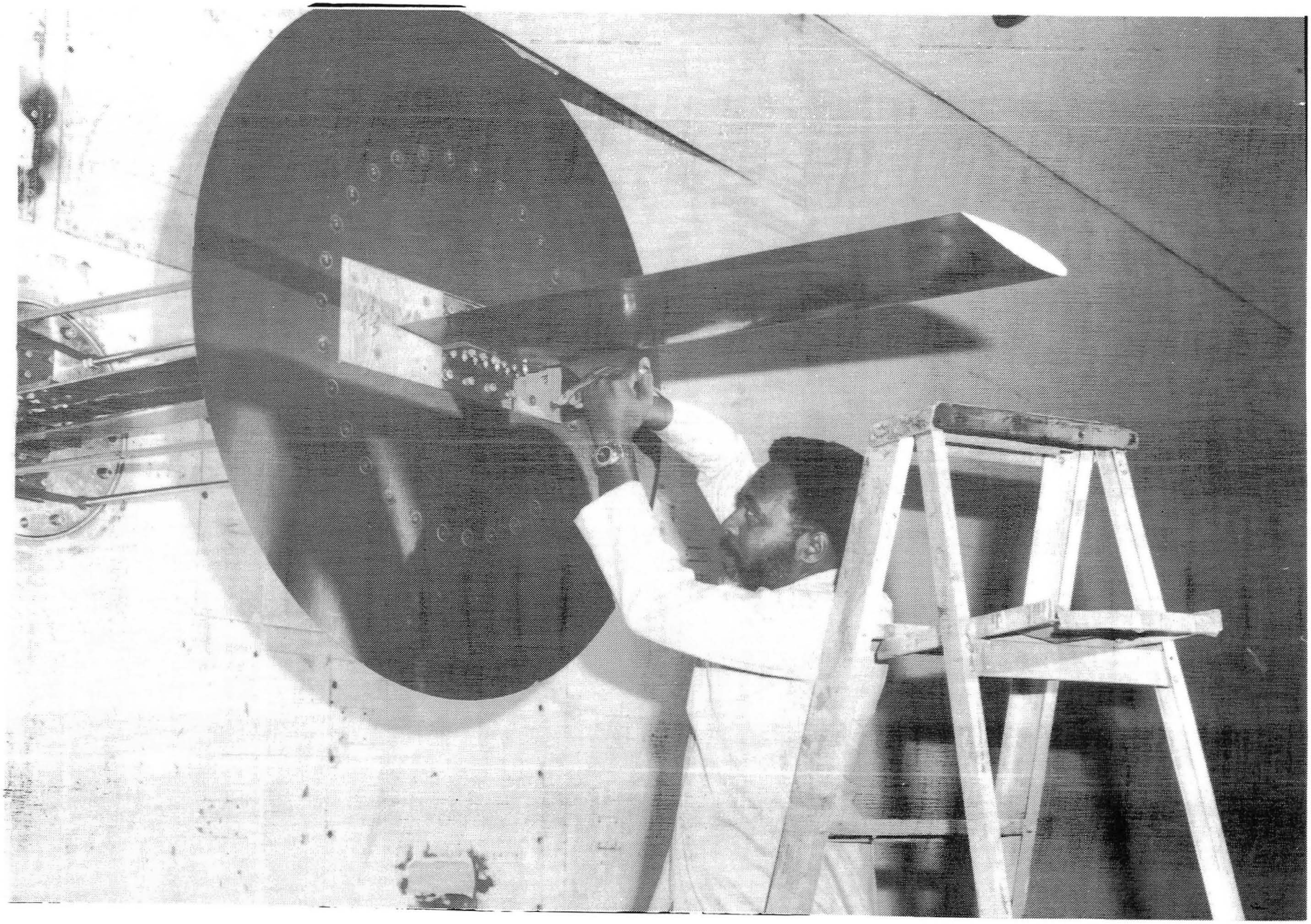

Figure 4.- A wing installed on the mount system in the wind tunnel.

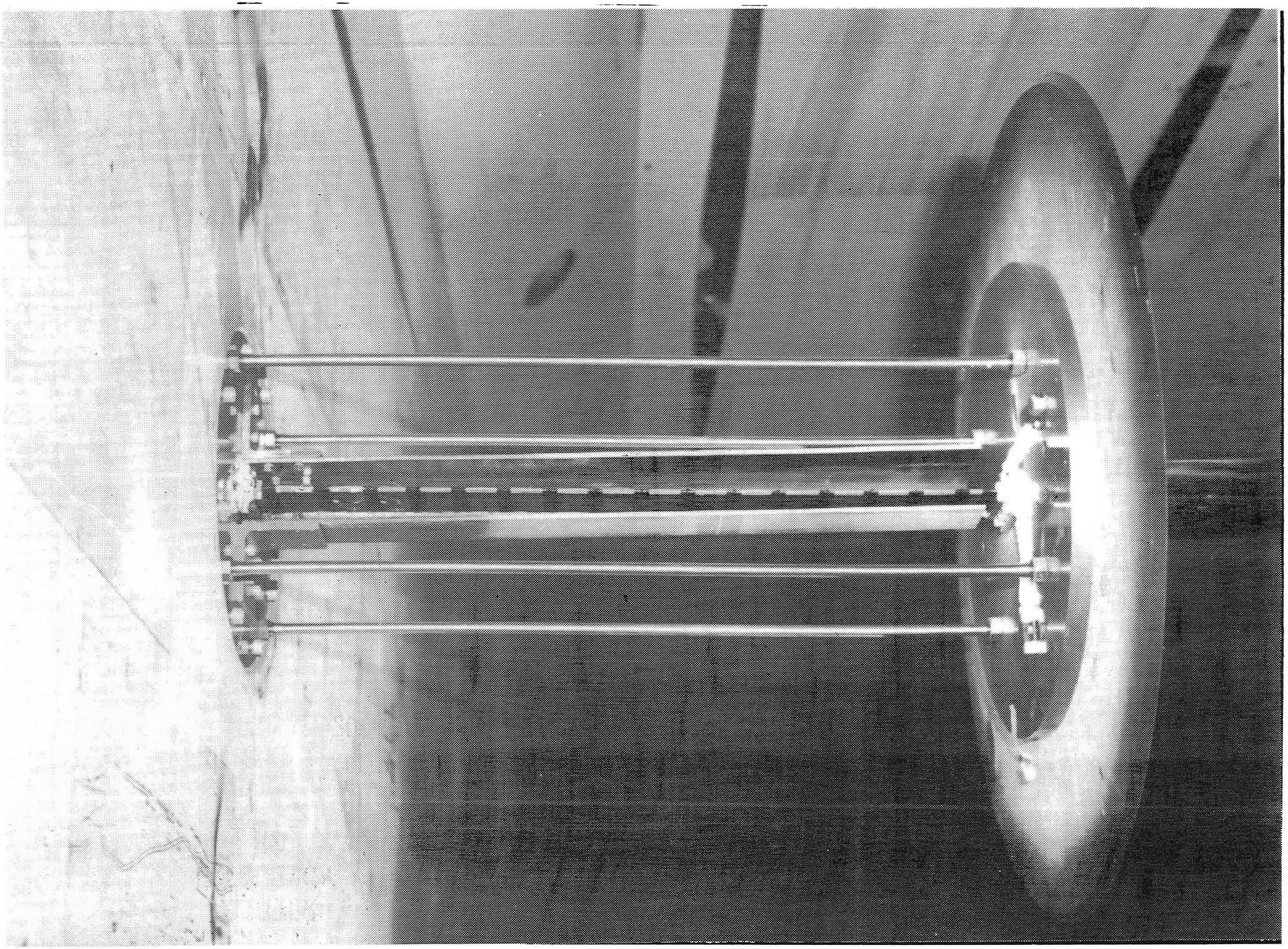

Figure 5.- View looking upstream at the rods, drag strut, and windscreen.

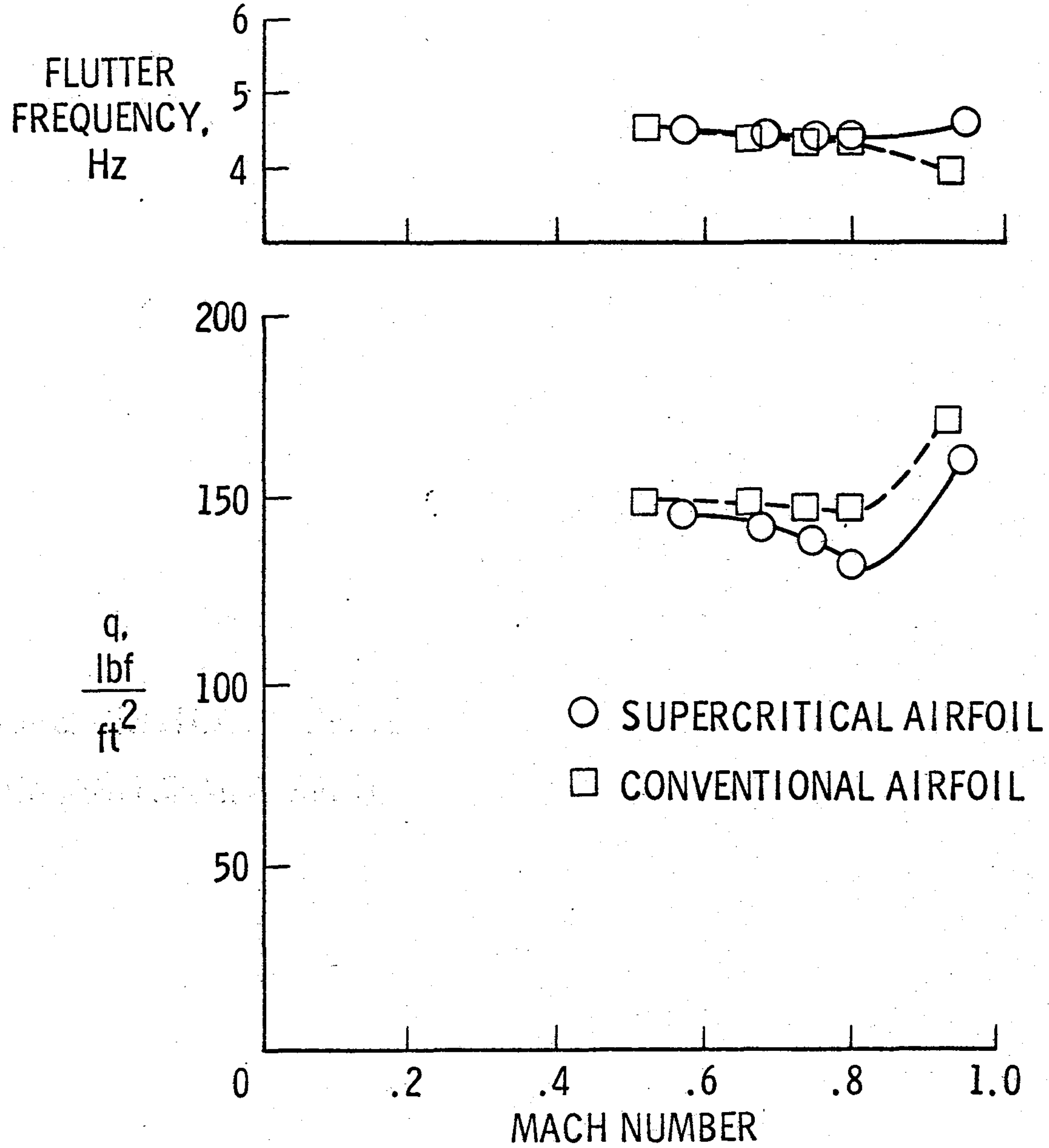

Figure 6.- Comparison of the measured low angle of attack flutter boundaries for two wings in freon.

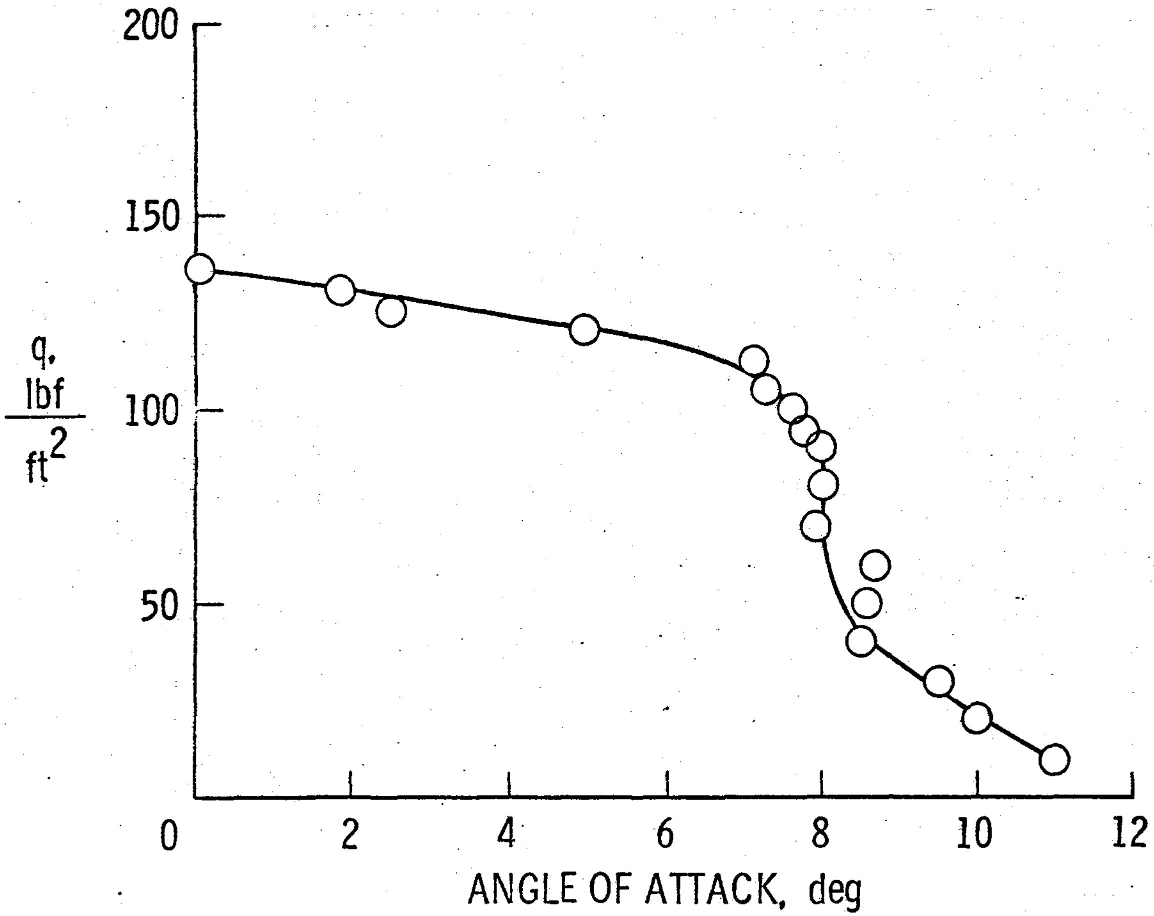

Figure 7.- Measured stall flutter boundary for the conventional wing at subsonic Mach numbers in air.

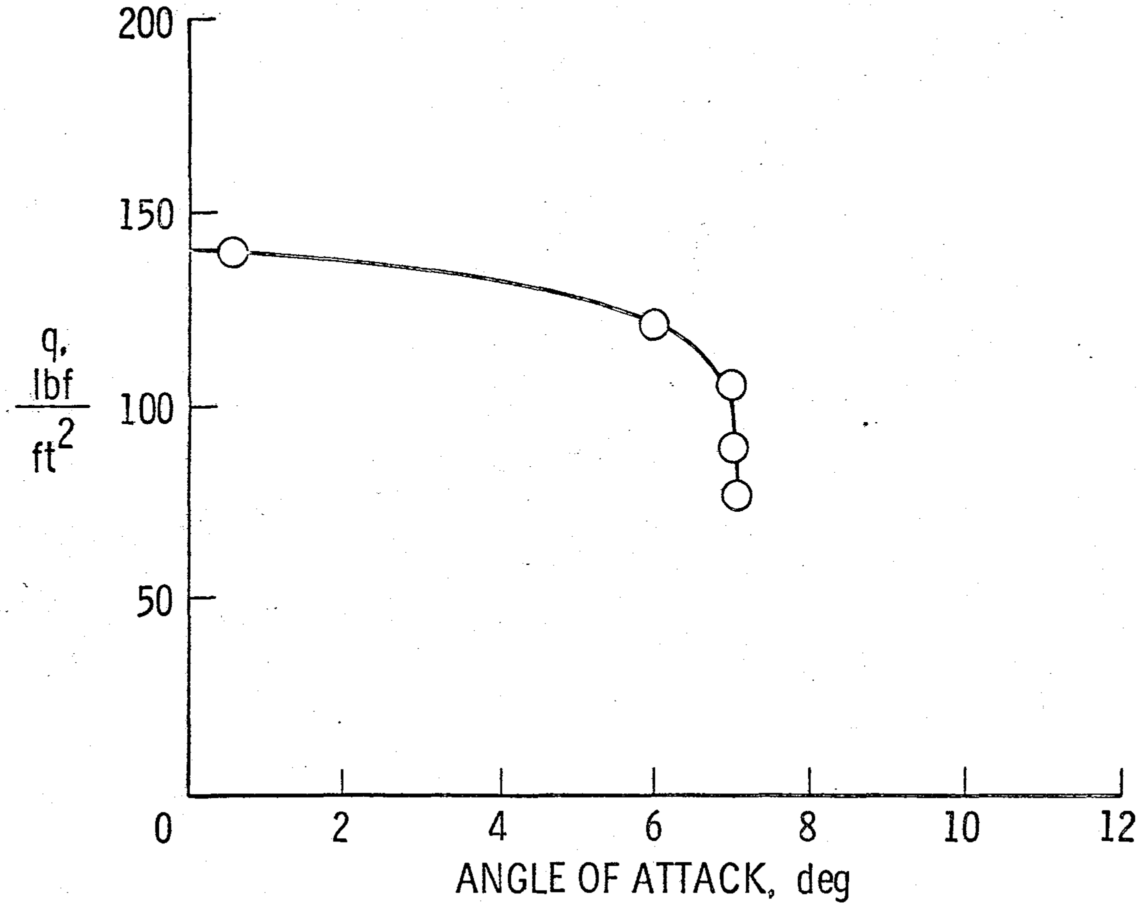

Figure 8.- Measured stall flutter boundary for the supercritical wing at 0.75 Mach number in freon.

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15. Supplementary Notes

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16. Abstract

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