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SOME CURRENT TECHNIQUES IN EXPERIMENTAL AEROELASTICITY

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ABSTRACT

This paper presents a brief review of some of the techniques currently employed in the transonic dynamics wind tunnel at NASA Langley Research Center to solve aeroelastic problems by use of dynamically and elastically scaled models.

INTRODUCTION

The advent of launch vehicles, with their new aeroelastic problems; and the increased use of large wind tunnels having the capability of wide variation in test conditions for studies of aircraft aeroelastic problems, has brought about the development of a variety of new testing techniques in which the model performs the role of a mechanical analog. The development of these techniques has been intimately tied in with the ability to produce test conditions to which it is possible to scale models which yield meaningful quantitative results. Regier discussed the design and application of such models at the ASME Winter Annual Meeting in 1963 (1)**, and Guyett has reviewed the subject recently in (2).

This paper will describe briefly a few of these techniques currently employed in the transonic dynamics wind tunnel at the NASA Langley Research

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**Numbers in parentheses refer to similarly numbered references in bibliography at end of paper.

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Center and discuss some of the practical aspects which may be of importance in the use of these methods. The areas to be discussed include: launch vehicle buffeting and ground wind loads, aircraft flutter and gust response, aircraft static aeroelasticity, and deployment loads of flexible lifting devices. While some of these techniques have been described elsewhere, (3) through (7), this paper will serve to bring together some of the highlights and will provide an indication of the state-of-the-art in this important field.

LAUNCH VEHICLE BUFFETING

Techniques for studying launch vehicle buffeting have been reviewed recently by Hensel (8) and Rainey (9). As pointed out, some phases of this problem are characterized by very complicated structural behavior of systems exposed to multiple random inputs. Prediction of structural response may require difficult, if not virtually impossible, analytical programs.

The technique of using measured fluctuating pressure inputs to predict gross structural response leads to difficulties as mentioned above. A much more effective technique described by Hanson and Jones (3) makes use of a suitably scaled aeroelastic model, shown in figure 1, as a mechanical analog. The model, in effect, generates the correct aerodynamic inputs, performs the difficult time and space integrations, and then produces the desired response. Such a performance by the model is possible only through the use of a mounting which permits a near simulation of the vibratory modes of free flight which are important to this problem.

This mounting system used in (3) to study transonic buffeting loads is shown in figure 2. Briefly, it consists of a sting on which the model is supported through a system of cables and springs. Leaf springs, shown in the figure, support the model at the forward and rear node points of the first free-free mode, restraining the model in the drag and yaw directions, and providing a portion of the stiffness required to simulate the pitch frequency. The support cables shown are also attached to these node points through pulleys to support the weight. The cables run outside to adjustable torque springs which provide the remaining part of the pitch stiffness. The pneumatically operated snubbers were used as required to restrain model motion with respect to the sting. A vital feature is the electromagnetic shaker used to excite the model in its elastic vibration modes in order to determine the aerodynamic damping in each mode.

Another launch vehicle problem in which difficult analytical procedures are circumvented by means of the mechanical analog technique will be discussed in the following section.

GROUND WIND LOADS

Engineering analysis of fluctuating loads produced by ground winds on slim vertically mounted cylindrical structures, such as smokestacks, is not new and has been handled effectively by designers for many years. A new emphasis on this old problem has been sparked by the advent of launch vehicles having much more complicated aerodynamics. The high degree of structural efficiency required in these designs and the relatively great risk involved necessitates an accurate quantitative knowledge of the loads imposed by ground winds while the vehicle is on the launch pad. The advantages of studying the problem with wind-tunnel models rather than on full-scale vehicles are obvious. Analytical difficulties comparable to those of the buffeting problem again encourage the use of the mechanical analog.

A technique described by Hanson and Jones also in (3), is physically quite simple in principle. The dynamically and elastically scaled model is mounted vertically on a massive turntable as shown in figure 3, which provides a convenient means for changing relative wind direction. The model is instrumented for measurement of both steady and unsteady components of wind-induced loads. These loads consist of a steady drag component acting in the direction of the wind and an unsteady normal component resulting from vortex shedding. Test conditions are scaled to simulate as closely as possible the velocities of steady winds without attempting simulation of the complex turbulent characteristics of the atmosphere. Simulation of the variation of wind speed with height has been attempted recently in one investigation by the installation of a series of horizontal circular bars upstream of the model as shown in figure 4. Spacing of the bars was designed to give a specific velocity profile. Preliminary results shown in figure 5 indicate good agreement in the upper part of the test section but show the need for adjustment in bar spacing in the lower part.

There are several aspects of this technique which may be of interest. One involving damping has been one of the most troublesome factors in the program. Launch vehicles in general are lightly damped structures, and the amount of damping has an important influence on the dynamic response. Although by no means unique to this program, consistently duplicating the structural damping throughout the test has been a difficult modeling and operating problem. The development of a self-contained viscous damper provided a workable but inconvenient means of controlling the damping. An early version of this damper consists of a cylinder filled with viscous oil and a number of lead discs resting on concave trays in the cylinder as shown in figure 6. As the model oscillates, the combined action of the oil and the weights provides a means of energy dissipation. The amount of damping may be varied by using oil of different viscosity or by varying the number and weight of the lead discs. An improved version, also shown in figure 6, employs the same principle but with greater effectiveness through the use of a tunable rod mounting for the outer case. The effectiveness is increased to the extent that only one lead disc is needed. By tuning the system to respond to frequencies approaching that of the first bending mode of the model (but not close enough to alter the mode) damping coefficients may be obtained which are adjustable to cover a range of values anticipated for the full-scale vehicle.

A system which permits remote variation of damping has been developed by Chang of Lockheed Corporation, Huntsville, and used recently with greatly improved testing efficiency. The arrangement, shown schematically in figure 7, consists essentially of two electromagnetic shakers mounted perpendicularly on a low-frequency central support column fastened to the turntable and extending up inside the model. The movable coils were connected to the model structure through flex pivot attachments. Integrated outputs of accelerometers sensitive to motions in the respective directions of shaker motion are applied in feed-back loops to the shaker control circuits to produce opposing forces proportional in controllable magnitudes of motion. Calibration of the system permits quantitative knowledge of the damping force applied during the test. Dangerous amplitudes of model motion can thus be prevented by greatly increasing the magnitude of damping.

An interesting readout technique has been developed for these tests which is quite simple and effective. Time exposure photographs are made of an oscilloscope display of the output of strain gages mounted near the model base station in planes 90° apart around the circumference. As shown in the schematic diagram in figure 8, maximum values of drag and lateral force are indicated by the size of the elliptical figure formed by the trace of the light spot. The static vector and maximum resultant vector, which is a measure of the maximum resultant bending moment, are measured as shown from the no-wind position of the spot. This presentation gives a quickly obtainable record which shows the correct relationship between the maximum oscillatory response in the lateral and drag directions. Examples of the oscilloscope presenatations are shown in figure 9.

Other techniques more applicable to aircraft problems will now be considered. One technique which is thought to be an important advancement in mounting will now be described.

TWO-CABLE MOUNTING SYSTEM

One generally accepted fact in transonic wind-tunnel testing of dynamic-aeroelastic models is that the mounting system is not the least of the problems. This is particularly true for complete aircraft models in which body dynamics may play an important role. The ideal system is one having no restraint or, in effect, a free-flight system. The practical system seeks to approach this ideal in at least the aspects most important to the test at hand. Some desirable features which such a mounting system might have are:

1. A soft support such that the natural frequencies associated with the mount are well below those of the free-flight and elastic modes.

2. Allow freedom of movement of sufficient amplitude for normal model motion due to turbulence, trim changes, and the like.

3. Moving masses associated with the mount should be negligible in effect relative to the total mass of the model.

4. Aerodynamic interference should be low.

5. Convenient trim adjustment and safety devices.

6. Predictable static and dynamic stability under all operating conditions.

7. Simplicity.

The two-cable mount system, described in some detail by Reed and Abbott in (4), incorporates most of these desirable features. Basically it is a very simple arrangement as illustrated schematically in figure 10. Two loops of small-diameter cable extend in mutually perpendicular planes from the model to the tunnel walls, one loop upstream and the other downstream. The cables pass through pulleys located within the fuselage contour, as shown in figure 11, and tension is applied by stretching a soft spring in the rear cable (and front cable, if necessary). The small-diameter cable causes little aerodynamic interference and negligible mass, compared with the total mass of the average model. The low spring stiffness of the system results in low natural mount related frequencies while permitting large translational and rotational motions.

Remotely operable trim control is desirable to keep the model centered in the tunnel because of changing flow conditions throughout the test range and other factors. Pitch and roll control are usually sufficient, and a single operator can fly the model using a miniature airplane-type control stick which positions the model control surfaces.

There are some aspects of trim control which may be troublesome, and although not unique to this system, must be given careful consideration. For models in which stiffness is scaled, the effectiveness of the surfaces may suffer from aeroelastic effects in a manner similar to that of the full-size aircraft. This fact may seriously handicap the model pilot's ability to keep the model in trim in some parts of the test range. For example, flutter models which have to be flown to a "margin boundary" which is considerably above the simulated normal flight boundary may understandably have serious aeroelastic problems such as aileron reversal. In designing such models, the estimated characteristics of the airplane should be considered in this respect, and, if necessary, provisions should be made for auxiliary trim devices. Translation of the cable attachment points relative to the tunnel airstream, effectively tilting or twisting the axis of the system, is another way to provide a limited amount of auxiliary trim control.

Keeping the model in trim through the transonic Mach number range where compressibility effects may cause rapid and drastic changes in the aerodynamic characteristics requires a reasonable amount of model piloting skill and experience. Anticipating these effects and varying tunnel speed very slowly in this range will greatly relieve the pilot's problems and avoid possible disaster. The value of experience for both the pilot and test personnel is one of several reasons why it is the practice in this facility to insist that tests of an expensive, fully scaled model be preceded by tests of an inexpensive "dummy" model; e.g., a model having approximately the same external geometry and overall mass properties but with no detailed mass and stiffness scaling.

Another aspect of the two-cable mount which requires careful consideration (as with all mounts allowing freedom of motion) is the stability of the system. The effects of improper choice of design parameters were demonstrated in a very spectacular manner during development when several types of instabilities were encountered. Equations of motion of the system have been derived, as discussed in (4); and a computer program in Fortran IV language is available by which the stability boundaries may be studied for any given model and a reasonably safe choice of design parameters selected. An element of uncertainty may still exist, however, in some of the information put into the analysis (the aerodynamic coefficients, for example); therefore, it is felt that this is another valid reason for recommending that the stability of the system be given a final checkout with the dummy model previously mentioned.

As an additional safety precaution, the model is attached to a quick-acting snubbing cable system, normally slack, which when actuated will apply damping to any motions and force sufficient to bring the model to the tunnel center. Either three or four cables in a Y or X arrangement are attached to the model, usually at an axial station slightly aft of the center of gravity. An incorrect position of attachment may also result in an unstable system when snubbed; therefore, the dynamics of the system should also be investigated for this condition.

This mounting system has proved very useful in transonic flutter testing of complete airplane models and is now being used as a rather essential feature of another technique now under development.

GUST RESPONSE TECHNIQUE

A technique is under development which it is hoped will prove of value in the analysis of gust loads on aircraft structures. It will provide a means of experimentally evaluating frequency response functions for a dynamically and elastically scaled wind-tunnel model, thereby enabling supplemental experimental information to be incorporated into the analytical program during the design stage rather than from later flight-test data.

Preliminary tests of the technique are described in more detail by Gilman and Bennett in (5). In essence the technique consists of measuring the response of an elastically and dynamically scaled model to an oscillating gust field generated in the wind tunnel by oscillating vanes located upstream of the test section. The arrangement, with superimposed schematic vane drive, is shown in figure 12. The vanes generate a nearly sinusoidal oscillating vertical component of velocity which may be varied in frequency from 0 to 20 cycles per second.

The scaled model is flown on the two-cable mount system described in the preceding section. This mount allows sufficient freedom for the model motions produced by the oscillator. If the geometry of the mount is properly selected, the effect of the mount on the model stability modes pertinent to this problem is small and may be accounted for as described in (5) to interpret the results in terms of a model in free flight.

Thus far the technique has shown promise but further evaluation is required before its usefulness is fully determined. Some of the evaluation problems are concerned with calibration of the oscillating airstream and determination of airstream inputs while other problems concern readout and reduction of data. Then, of course, there is the fundamental question of the philosophy to be employed in interpreting model data in terms of the full-scale airplane. Another consideration is also the limitations imposed by the equipment on both model scaling and on the scope of the investigation.

AIRCRAFT STATIC AEROELASTICITY

Investigations of aileron effectiveness using complete aeroelastic models of large subsonic jet transports have been carried out to Mach numbers well into the transonic range. It is noteworthy that these tests were made concurrent with flutter tests using the same flexibly mounted models. The aileron reversal boundary for each model was determined to Mach numbers considerably above the normal flight envelope. Such tests of relatively fragile aeroelastic models, on flexible mounts, through this range were difficult, but were successfully accomplished by a combination of teamwork, model piloting skill, and luck.

One type of mount used in these tests, described by Grosser in (6), is shown in figure 13. Although this mount is not aerodynamically clean, it provides two essential features; body freedom and a means for applying an external rolling moment to the model. The model is attached by soft, adjustable springs to two pylons on top of the sting. External static rolling moments may be applied to the model without changing any of the body modes by means of two push rods actuated by a roll mechanism. Rolling moments produced by the ailerons are balanced by a calibrated spring within the roll mechanism. The spring moments thus provide a measure of the rolling moment produced by incremental deflection of the ailerons. A sample of the results for one investigation, compared with some measured flight results for the airplane, are shown in figure 14.

As with the two-cable mount, trim control was provided by a pilot who controlled the model ailerons, auxiliary roll control, and stabilizer to keep the model within the limited range between stops. In addition, supplementary pitch trim was provided by changing sting angle. A pneumatic device was provided to quickly boost the model away from the stops. The necessity for this device and the importance of body freedom was impressively demonstrated during one of these tests. Although no free-flight-type flutter was encountered up to the simulated margin boundary, when the model changed longitudinal trim enough to force it against the stops, temporarily restricting body freedom, an unexpected violent wing-body coupled flutter mode was encountered. The boundary for this mode was apparently considerably below that to which the tests had to be carried. The pilot was thus in a very dangerous situation at the extremes of the test when he was far above this boundary. Instant diagnosis and correction were required to avert model destruction.

A technique has been developed recently for determing the aileron reversal boundary with the model mounted on the two-cable system. The principle is essentially the same as that used with the sting-pylon system but with the advantages that the model is allowed more freedom of motion and has less aerodynamic interference from the mount. In using this technique, the rear cable attachment points are translated in opposite directions normal to the airstream, thereby effectively twisting the system about the roll axis. External rolling moments, applied in this manner to keep the model in trim as the ailerons are deflected, are determined analytically from measurements of cable forces on the model and the geometry of the system. Test results of the same model using this technique are in reasonably good agreement with those using the sting-pylon mount (fig. 14).

DEPLOYMENT LOADS

One investigation of a somewhat different nature was the measurement of deployment loads experienced by a dynamically scaled inflatable parawing model. This parawing was deployed and inflated from a model spacecraft capsule mounted in a manner to allow rotational freedoms but restrained in translation. This work is described in (7) by Kelly and McNulty and the model is shown in flying attitude in figure 15. The purpose of this investigation was to evaluate the feasibility of using such a technique in a wind tunnel and to define problems. Comparison was made with a model in free flight by a series of deployments from a free-falling capsule dropped from a helicopter. Surprisingly enough, the wind-tunnel test correlated quite well in most respects, except for capsule motion. The main problems of the wind-tunnel investigation seemed to be stability and reliability. Lack of stability of some of the configurations, though no problem in the flight test, resulted in numerous failures during the wind-tunnel program, in some instances probably influenced by the lack of the translational freedom present in flight. Since deployment and inflation require several carefully timed steps, reliability of the equipment proved to be an important consideration.

Load information of a more detailed nature is of current interest for application to nonrigid airborne vehicles. Attempts are being made to develop techniques for indicating quantitatively the magnitude of local loads in the fabric material of the aerodynamic surfaces under dynamic loading conditions. One investigation of this elusive problem by Redd at Langley Research Center (but not yet reported) has thus far shown encouraging results. He has under development a strain-gage-type load cell which may be used to measure the bidirectional components of force in a fabric-type material. The cell is simply a small thin metal plate cemented on the fabric with orientation in the direction of weave. It was found desirable from a linearity standpoint to adjust plate proportions and strain-gage arrangement to obtain primary sensitivity to tensile forces. Interaction of the two components is determined by calibration in the usual manner, and temperature compensation is obtained by auxiliary gages. With location of the plate on the fabric at a sufficient distance from discontinuities such as seams and edges, static measurements very close to the true local forces have been obtained for the configurations tested.

SOME COMMENTS REGARDING MODEL CONSTRUCTION

Similarity laws demand mass and stiffness scale factors which often push the model designer to the limit of his resources, especially for the large airplanes of current interest. Even with the relief afforded by the use of heavy test mediums such as Freon-12, the usual model is a somewhat filmsy vehicle relative to the test conditions required. Problems resulting from inadequate engineering of seemingly minor parts have been difficult to cope with during the testing phase because at this stage it is not feasible to make basic changes in construction. Delays due to repeated failures of minor balsa fairings and covering sections, for example, can be as time consuming in some instances as the failure of a major structural part. In fact, no failure of a major part for lack of strength under normal test conditions can be recalled, but numerous hours of tunnel occupancy have been wasted because of failures of minor parts.

Other factors of equal importance are compatibility of materials and stability of structural properties with the test environment. An example of the troubles caused by incorrect choice of materials occurred recently during tests of a very nice looking flutter model of a current airplane. An efficient monocoque structure of reinforced plastic was stabilized in some areas by a lightweight plastic foam. An unfortunate choice of plastics was made, however, and the basic structural stiffness was found to be excessively sensitive to small temperature changes. Even with careful calibration and numerous temperature measurements an element of doubt as to the actual local stiffness existed throughout the test. In addition to this, the foam was not dimensionally stable with time when subjected to the low-pressure environment of the wind tunnel. A short-duration check had indicated that it was a satisfactory material, but the longer duration of the tunnel tests caused excessive shrinkage.

Cost considerations undoubtedly have an important influence on model design, for a good structural-dynamic simulation requires a large amount of engineering effort. Experience has shown, however, that care spent in careful design and construction is repaid many times over in a smoothly run test program.

CONCLUDING REMARKS

The few techniques reviewed in this paper are certainly not regarded as the final answer or necessarily the best methods of obtaining information in these several testing areas. They have been used successfully in the Langley transonic dynamics tunnel and could probably be adapted, with improvements, to other research facilities if the need exists. Perhaps the one thing most evident in this sampling is that there is ample opportunity for versatility and inventiveness in this field as each new project presents its associated problems.

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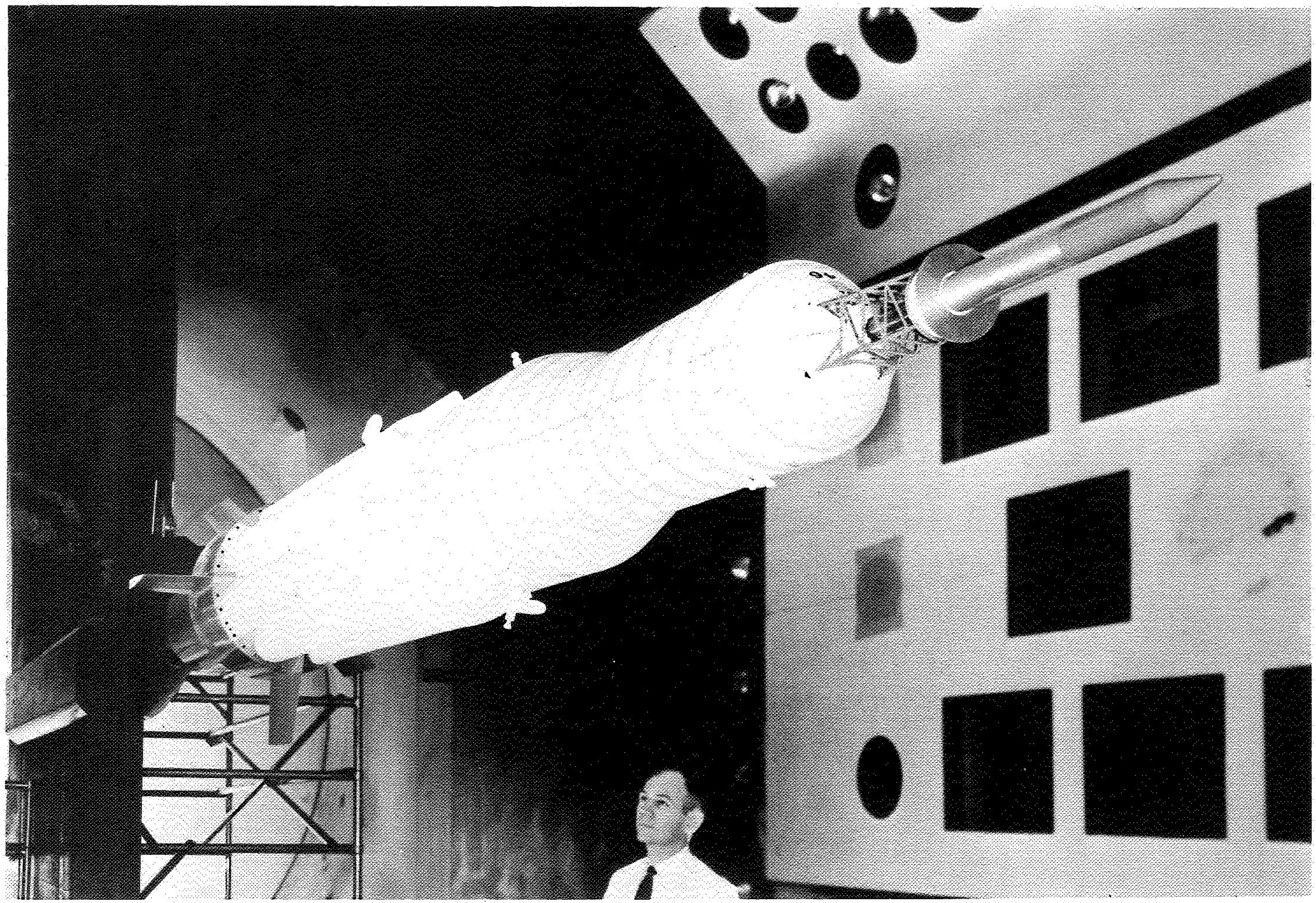

Figure 1.- Eight-percent aeroelastic buffet model mounted in tunnel.

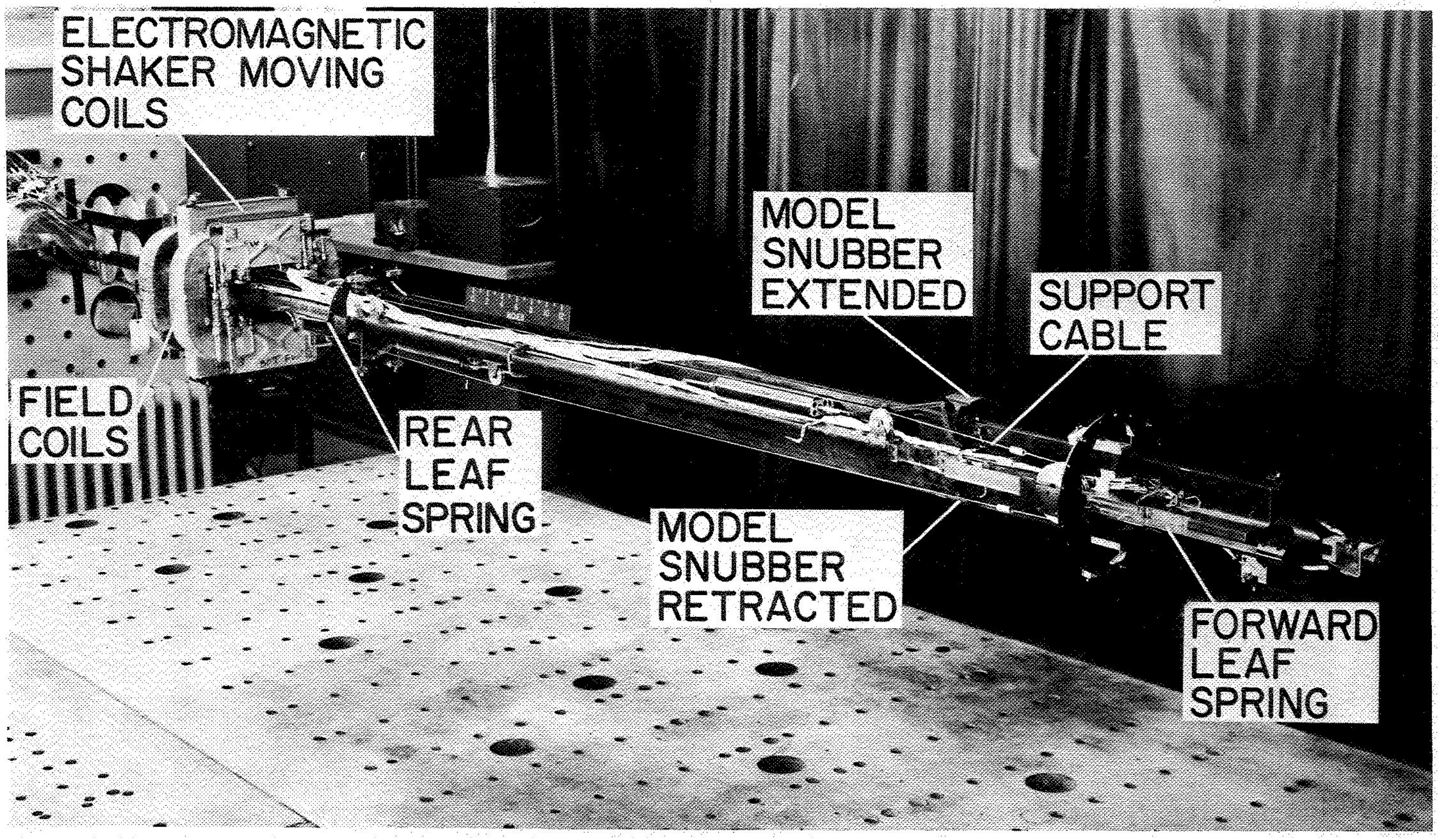

Figure 2.- Photograph of sting used for testing 8-percent Saturn-Apollo buffet model.

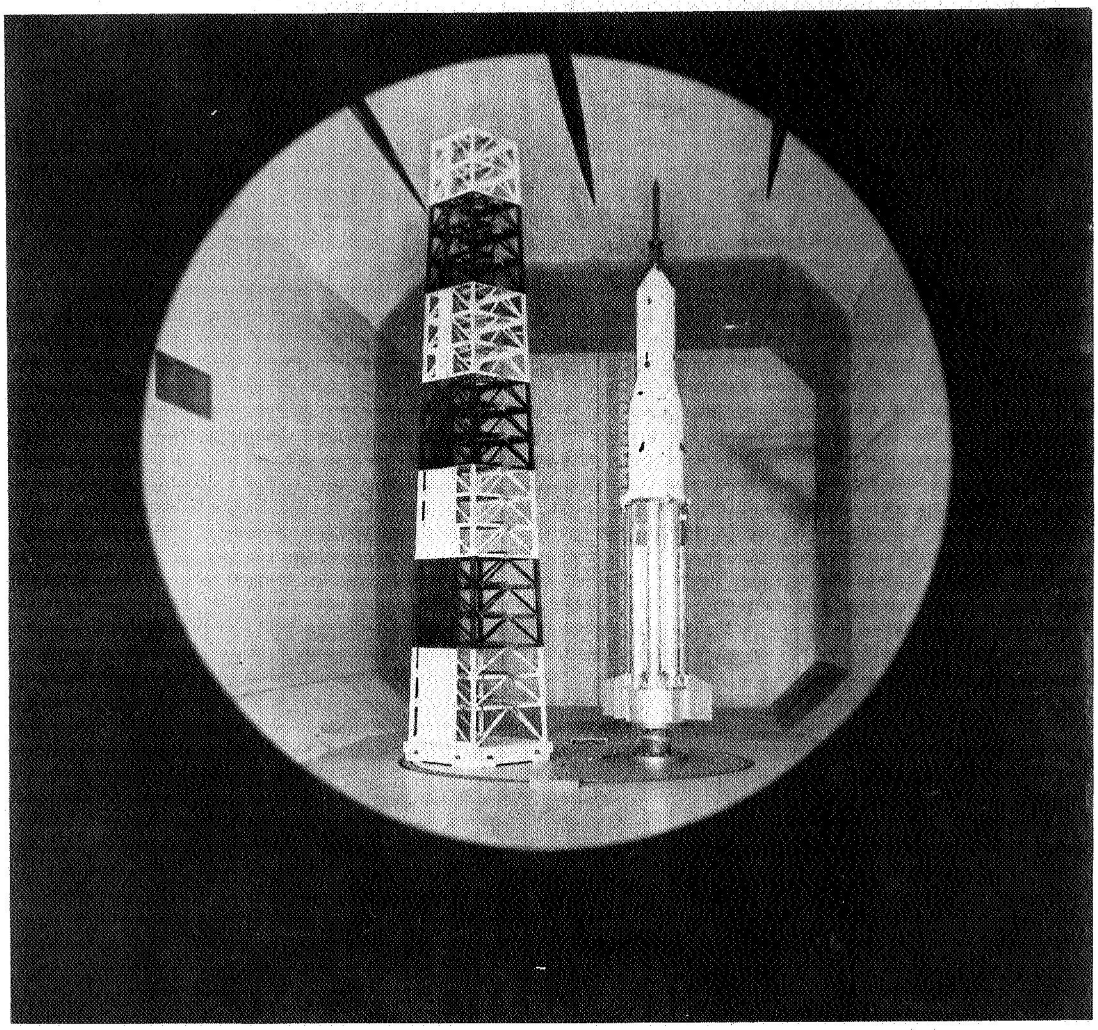

Figure 3.- Seven-percent scale Saturn 1-Block 11 ground-wind loads model.

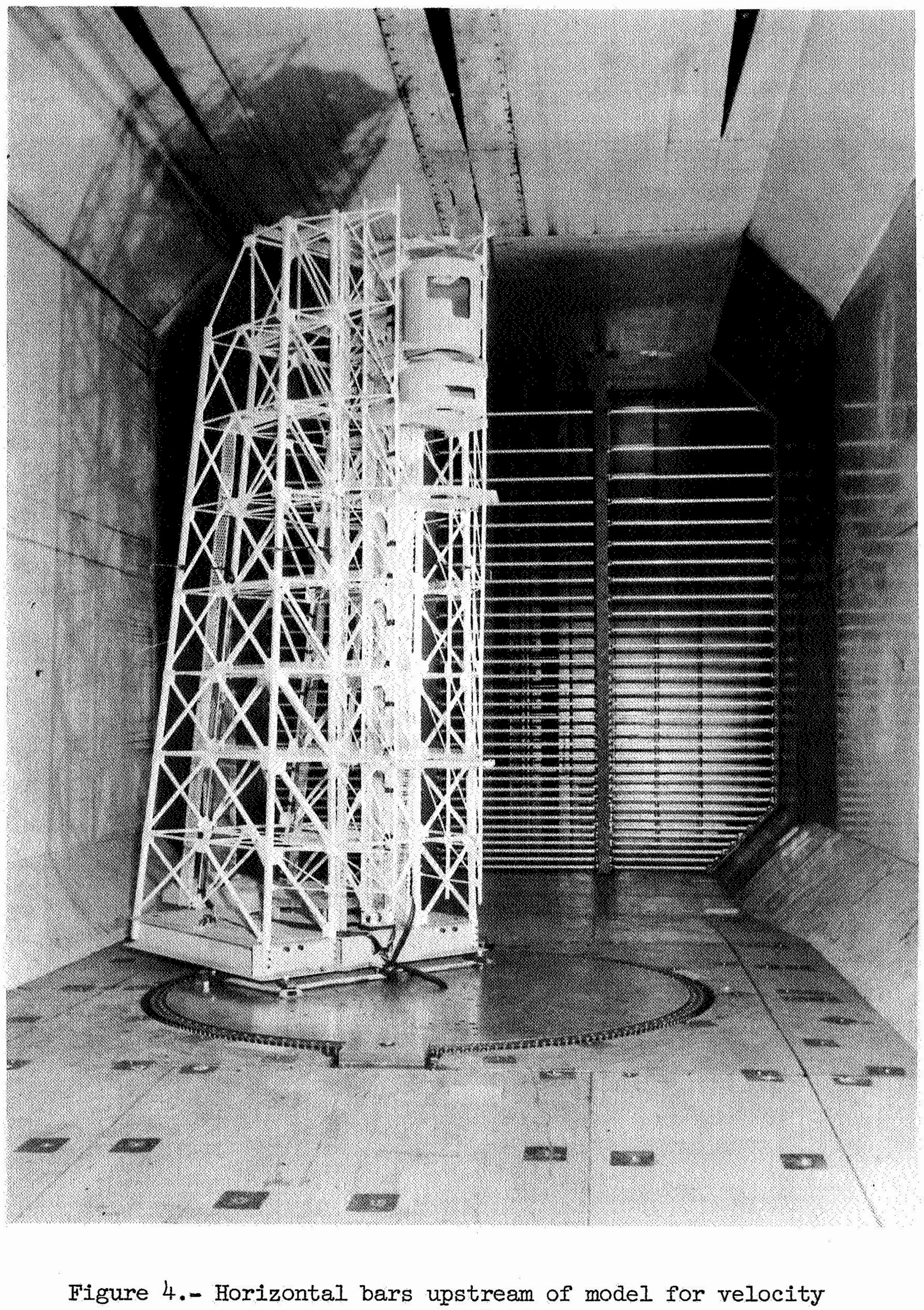

Figure 4.- Horizontal bars upstream of model for velocity profile simulation.

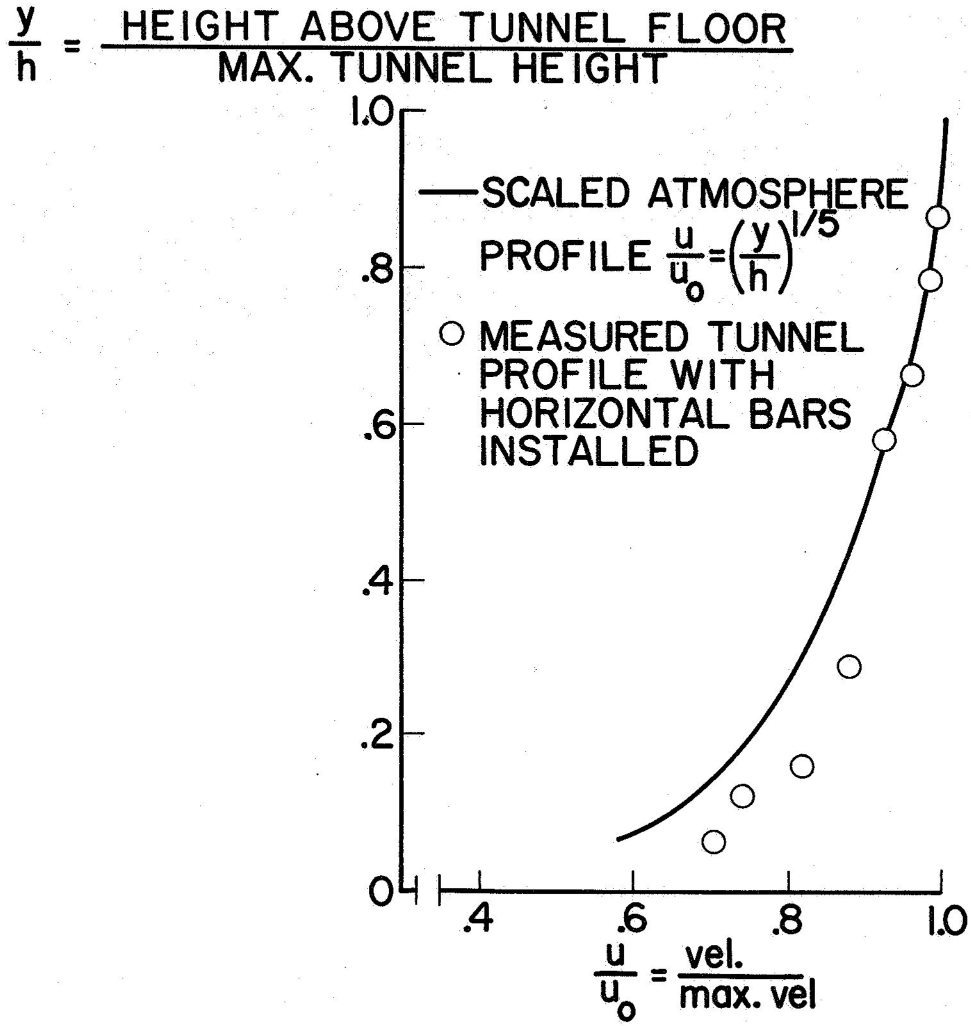

Figure 5.- Scaled atmospheric and simulated wind-tunnel velocity profiles.

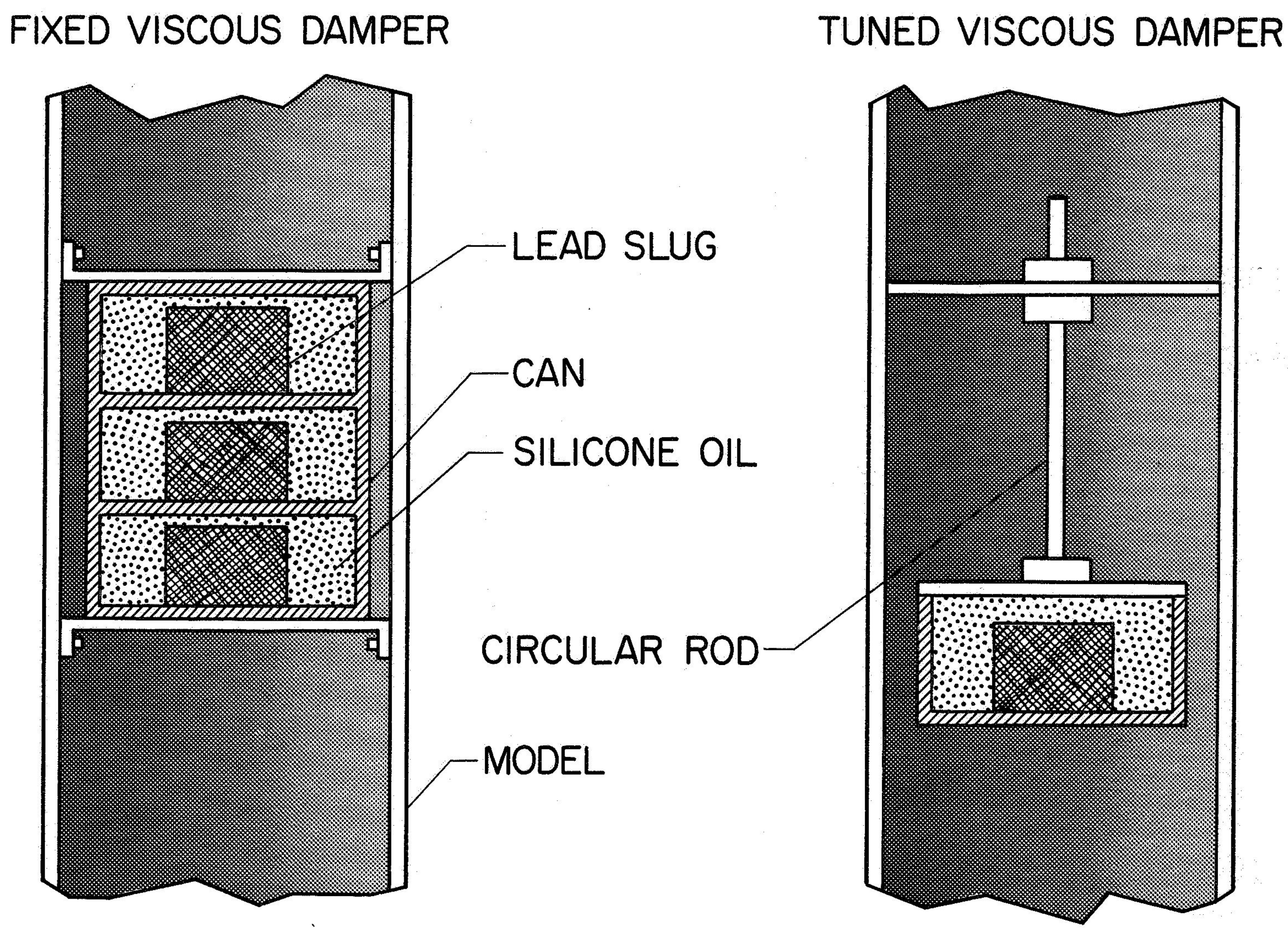

Figure 6.- Auxiliary dampers.

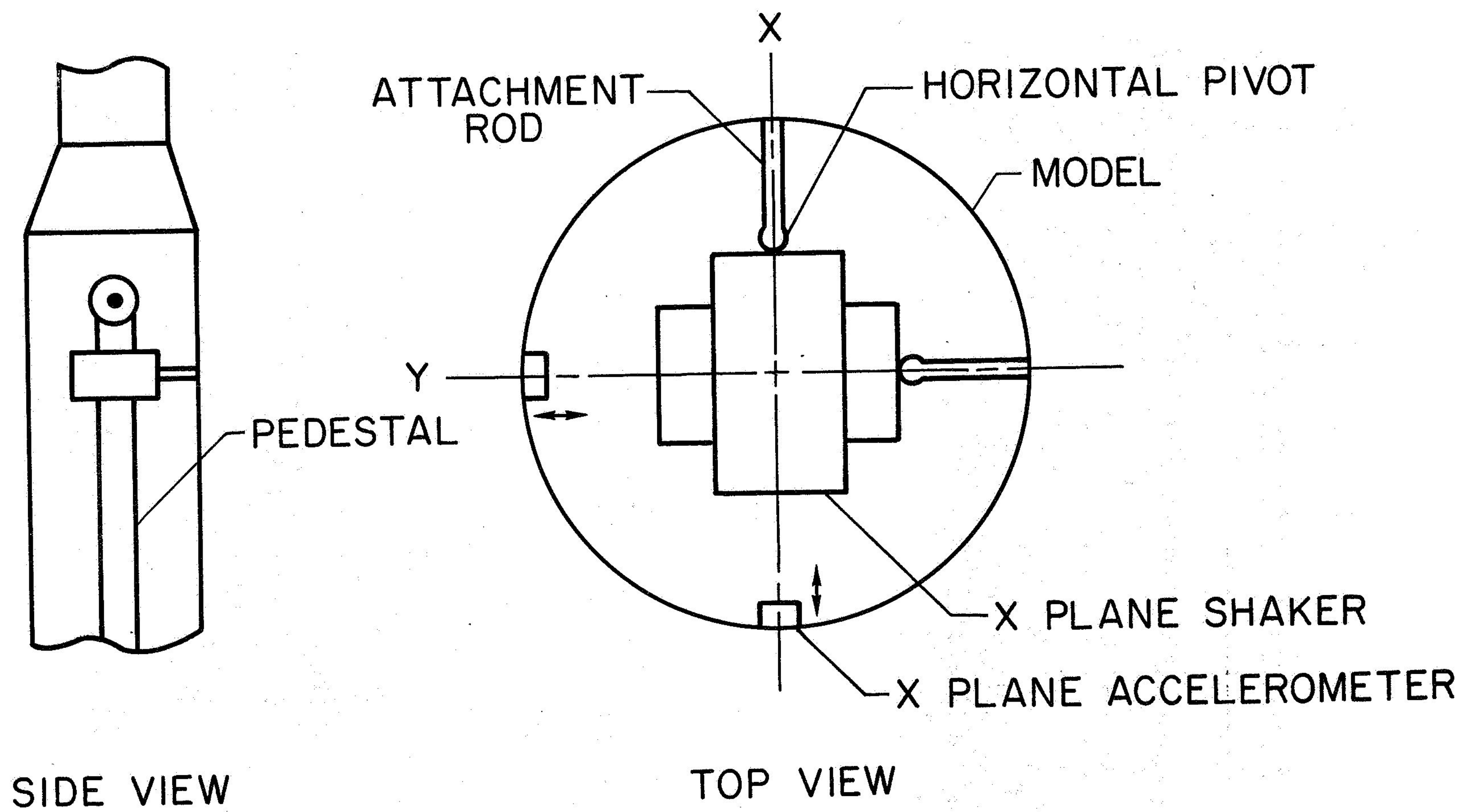

Figure 7.- Electromagnetic dampers.

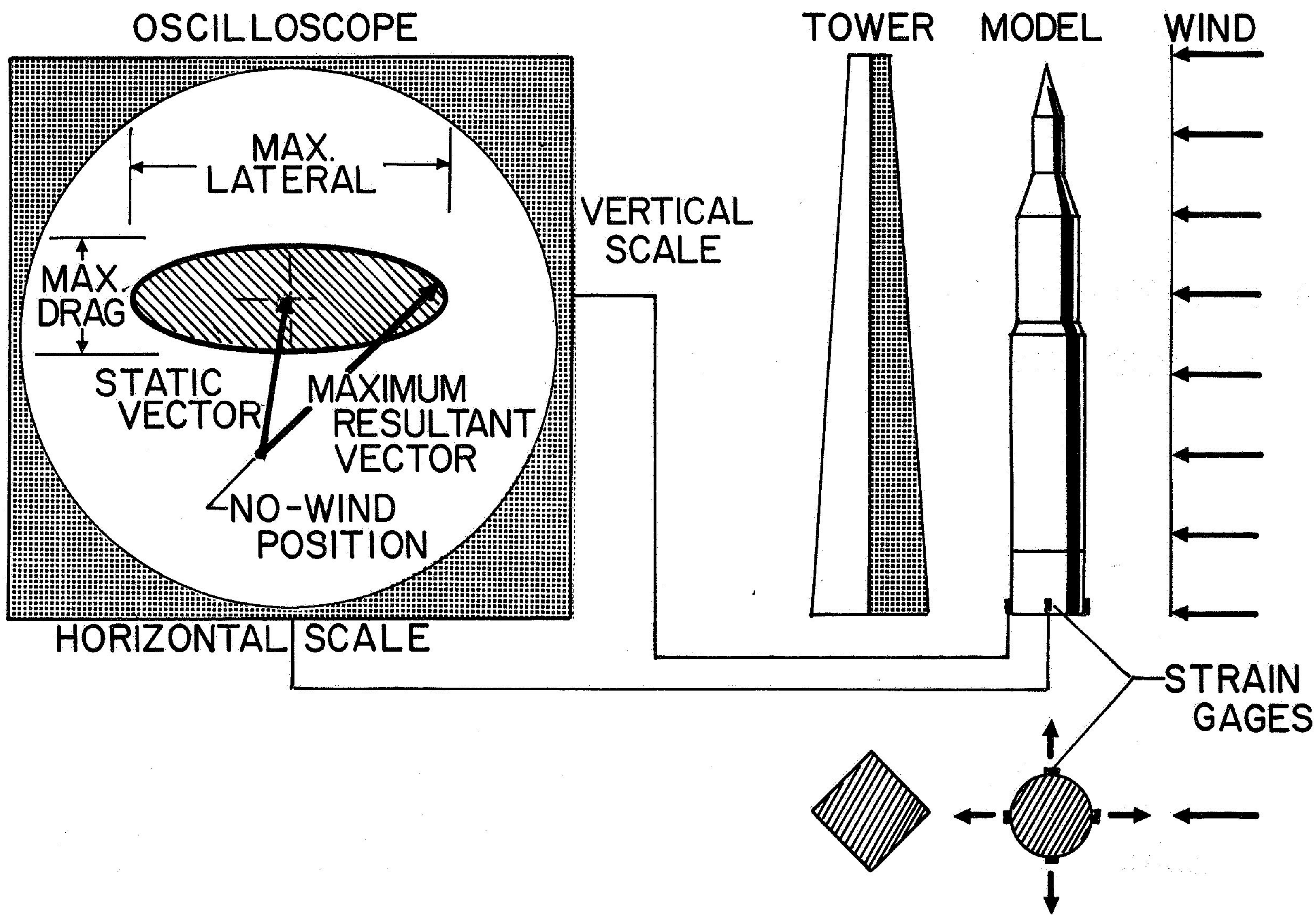

Figure 8.- Schematic of oscilloscope time history of base bending-moment response.

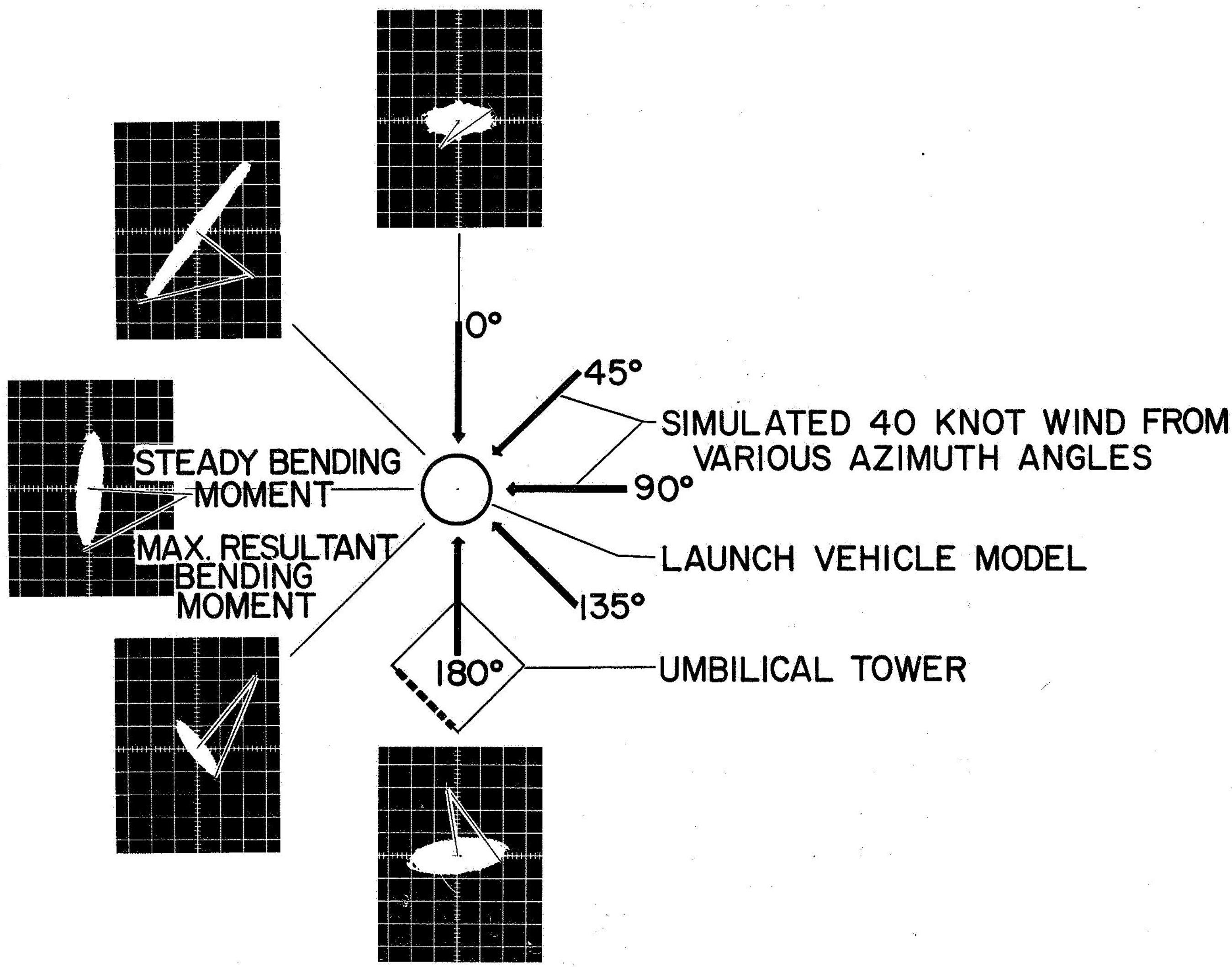

Figure 9.- Illustration of bending-moment response to winds from various azimuth angles.

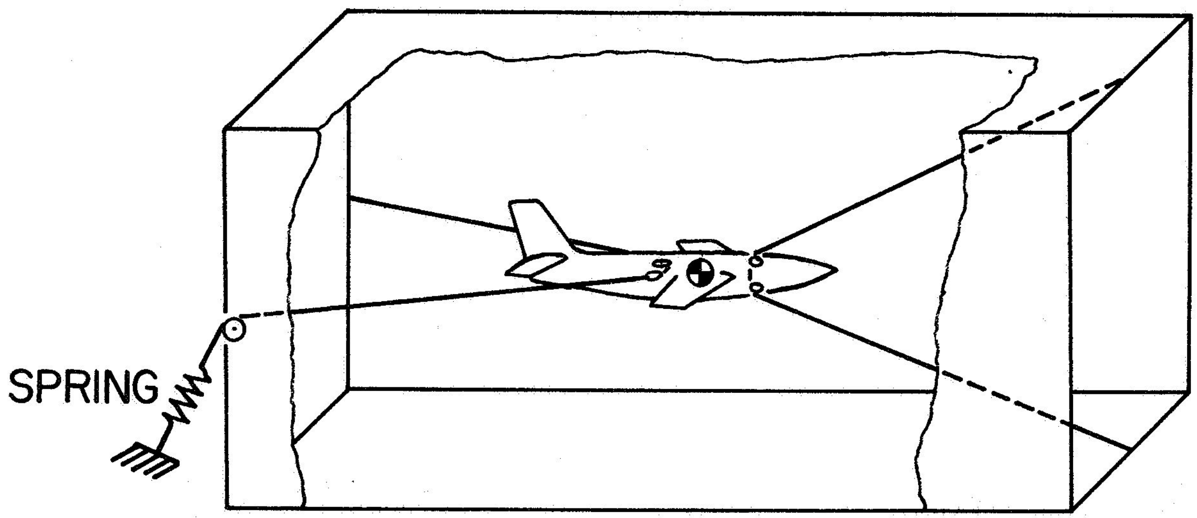

Figure 10.- Two-cable mount.

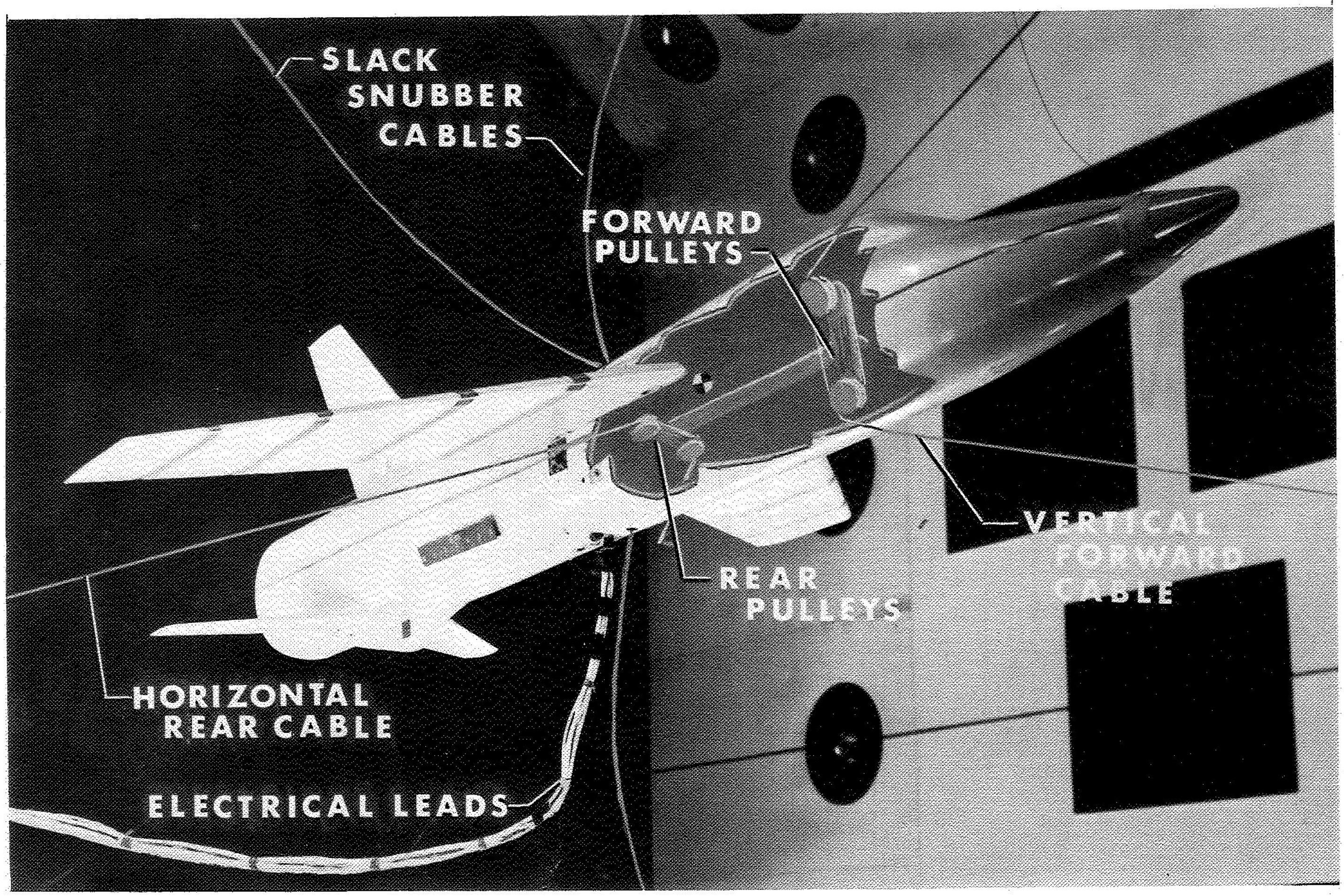

Figure 11.- Fighter-type model on the two-cable mount.

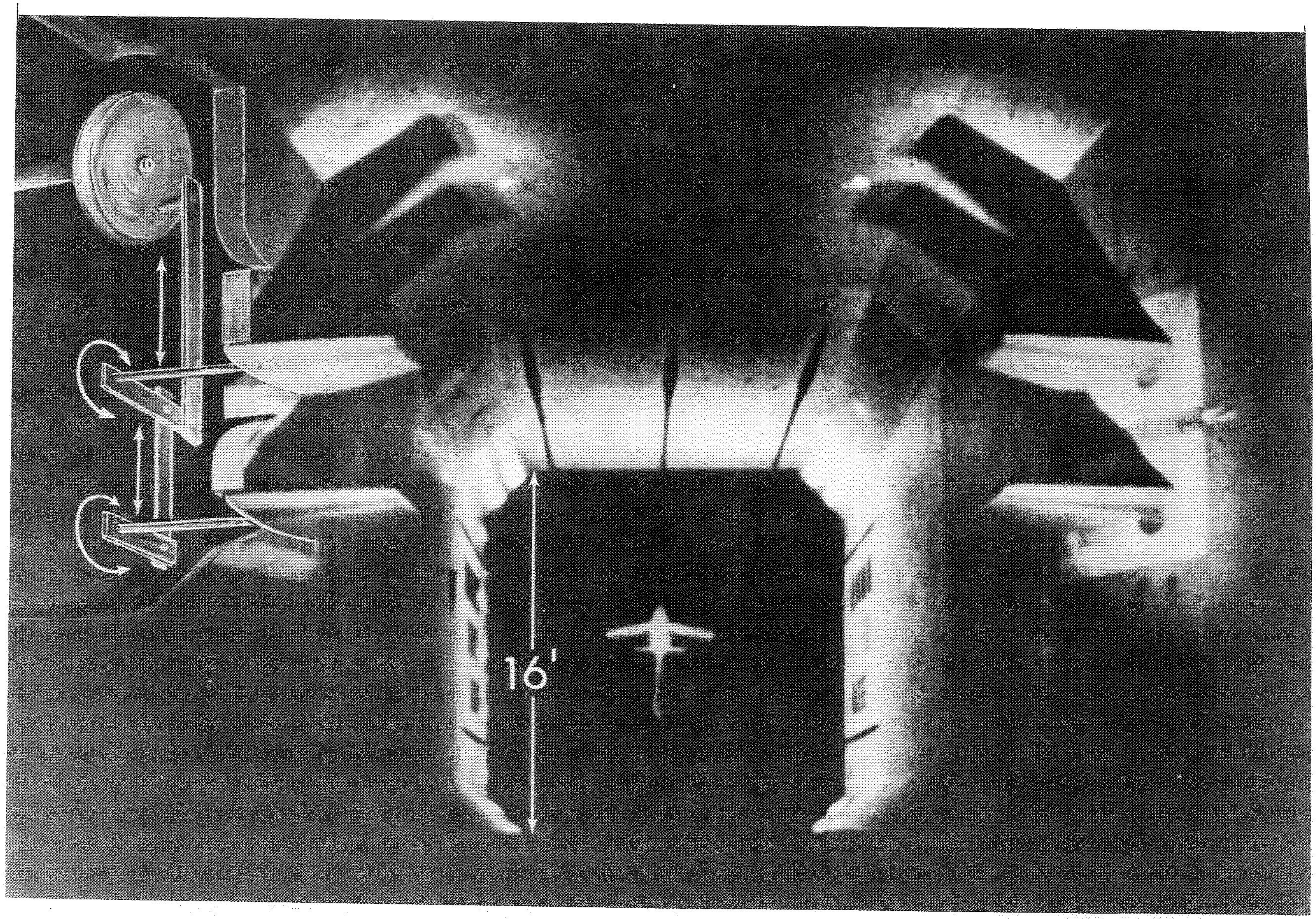

Figure 12.- Photograph of vanes and model in the Langley transonic dynamics tunnel with cutaway showing schematic of mechanism.

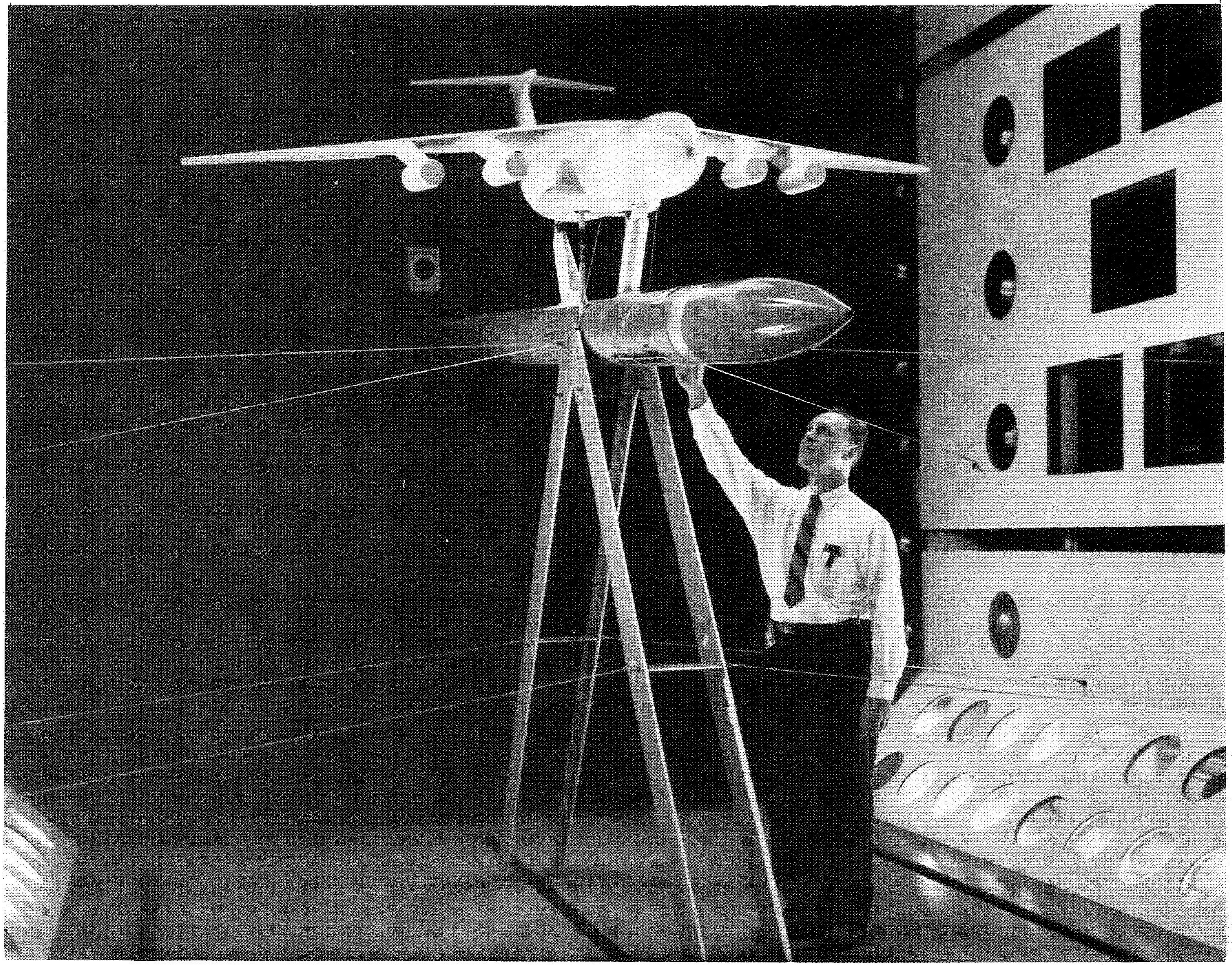

Figure 13.- Aeroelastic model on sting-pylon mount.

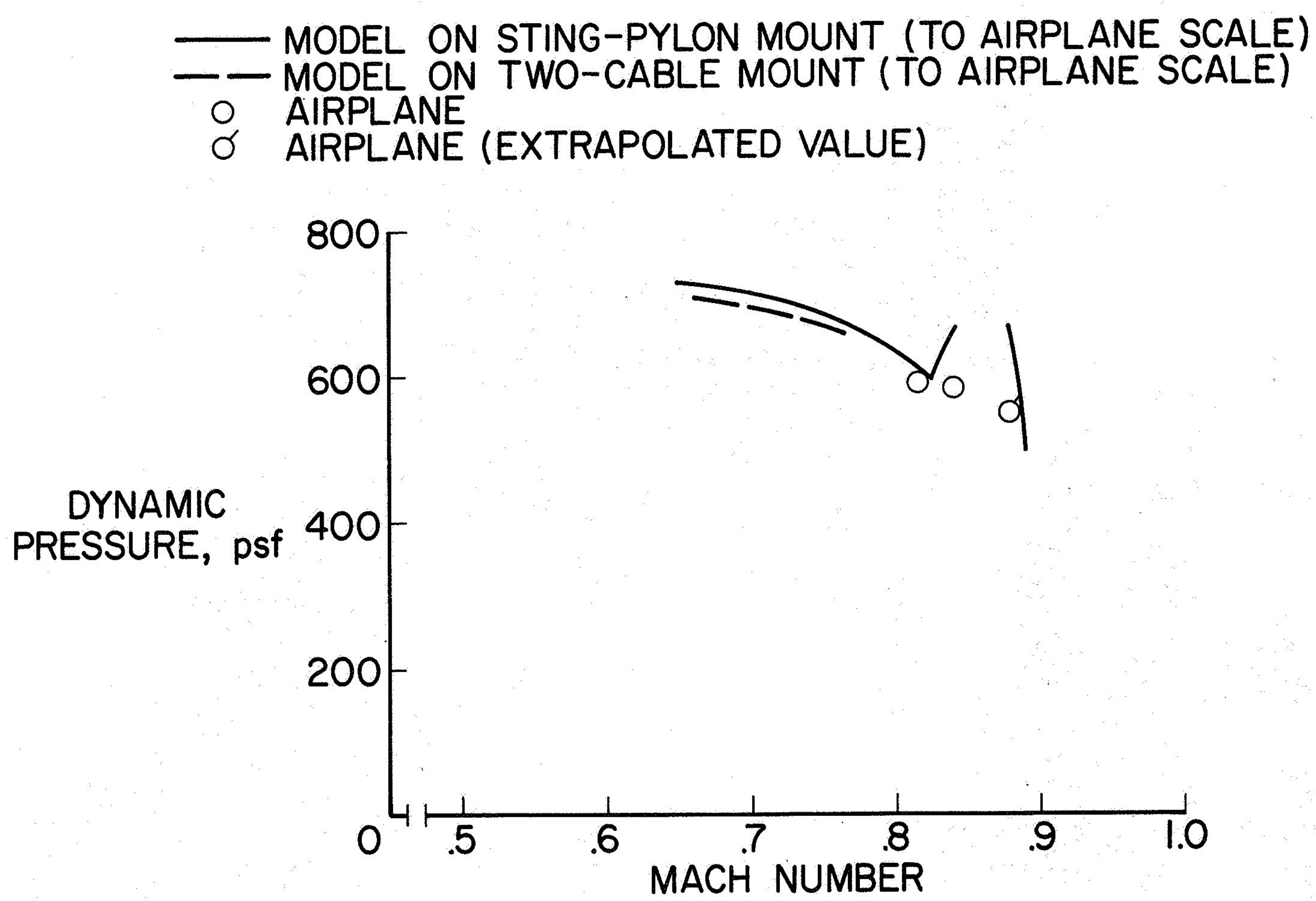

Figure 14.- Aileron reversal boundaries for model and airplane.

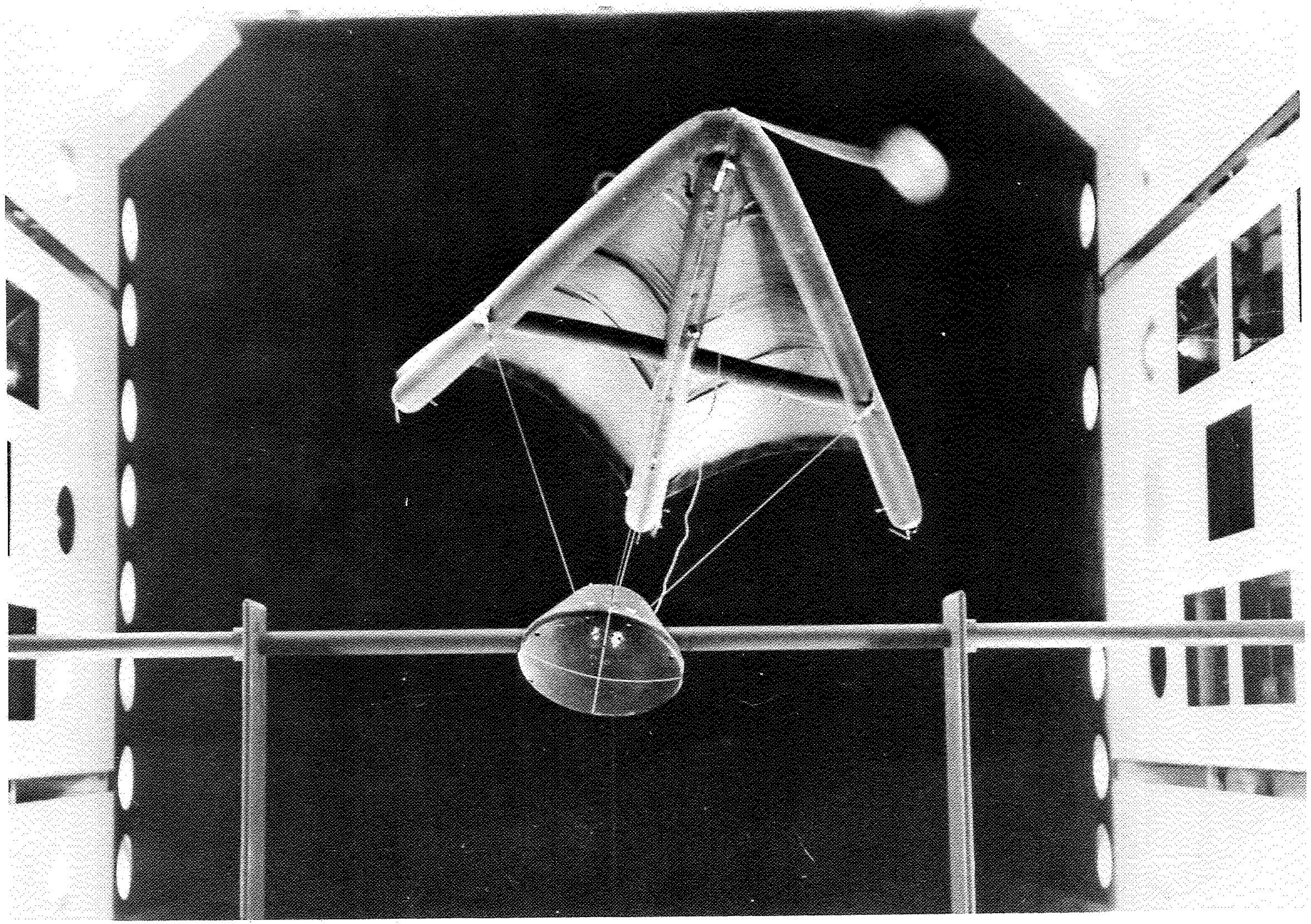

Figure 15.- Fully deployed parawing model.

NASA-Langley, 1967