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WIND TUNNEL MODELS

by

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This Report was presented at the Eighth Meeting of the Wind Tunnel and Model Testing Panel, held from February 20th to 25th, 1956 in Rome, Italy.

SUMMARY

This paper will deal with wind tunnel models, their design, and construction. It is based on experience gained by the Model Design Group of North American Aviation, Inc., Los Angeles Division, as observed by the author and his associates. Only unclassified material is included. An attempt will be made to avoid giving data already published. It is hoped that this paper will be of value to those concerned with wind tunnel models, particularly to those connected with model design and construction.

SOMMAIRE

Cette communication a pour sujet, les maquettes, essais en souffleries, leur conception et leur construction, d'après les connaissances acquises par le Model Design Group of North American Aviation, Inc., Los Angeles Division, commentées par l'auteur et ses collaborateurs. Seuls les travaux n'ayant pas de classification de secret sont mentionnés.

L'auteur s'est efforcé de ne présenter que des études non encore publiées il espère que ce rapport présentera un intérêt pour les personnes ayant à concevoir, construire ou utiliser des maquettes de souffleries.

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R. P. Davie*

1. INTRODUCTION

1.1 Scope

This paper is based on the experience of the Model Design Group of North American Aviation, Inc., Los Angeles Division in the design and construction of wind tunnel models. Only unclassified material is included and an attempt has been made to avoid giving data already published.**

1.2 History

Even before the first airplane flight, wind tunnel models were constructed and tested. Early models were quite simple. They were usually made of wood, with metal fittings for mounting and for control surface attachment. Tunnel speeds were low, and strength problems were not critical. As airplanes became faster and more complex, corresponding advances were made in wind tunnel testing. Larger tunnels with greater speed were designed, capable of use for broader research. The dynamic pressure (a measure of model loads) rose from about 10 lb/ft^2 to over 1000 lb/ft^2. This increased dynamic pressure made it necessary to construct highly complex models of high-strength steel.

Development has been so extensive that design and construction of wind tunnel models has become a science in itself. Some notable milestones have been the use of water-cooled, electric-motor-driven propellers on models; the use of electric strain gages for model force measurement; remotely operated and position indicated control surfaces; the internal balance; the sting support; development of dynamic models of all types; and the evolution of duct inlet and internal flow models.

1.3 Reason for Models

Aerodynamic research is indispensable to aviation progress; and wind tunnel testing, a basic part of that research, requires models. Wind tunnel testing with models is much less costly and less dangerous than flight testing. Research can be done in greater volume, without risk to human life. Also, wind tunnel testing provides a great deal of information which can be gained in no other way; and with proper corrections, interpretation, and application, the data is very accurate.

North American Aviation, Inc., considers wind tunnel testing so important that it has a 7.75 ft by 11 ft subsonic wind tunnel, a 4 ft diameter subsonic wind tunnel, a

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**North American Aviation, Inc., Los Angeles, U.S.A.*

**Reference 1 contains valuable information on wind tunnels, tunnel testing, instrumentation etc., as well as on models. Its study, or an equivalent might be considered a pre-requisite for anyone wanting to go thoroughly into this field.

3.5 in. by 3.5 in. continuous supersonic tunnel; and a 16 in. by 16 in. intermittent vacuum sphere supersonic wind tunnel. A 7 ft by 7 ft blowdown 'trisonic' (subsonic, transonic, and supersonic) wind tunnel is under construction. North American Aviation also has a one-sixth interest in the Southern California Cooperative Wind Tunnel, a continuous tunnel approximately 8 ft by 11 ft, which will operate at subsonic through transonic and supersonic speeds, up to a Mach number of 1.8.

1.4 Types of Wind Tunnel Models

Depending on the nature of the information desired, there are various types of wind tunnel models which may be used. These may be divided into two basic categories - static and dynamic.

The static models are the most widely used type. They are of relatively rigid construction and mounting, and operate in a steady state of airflow. Usual measurements are forces, moments, pressures, etc., taken on the model and its components for determining aerodynamic characteristics. The actual weight and moment of inertia of the model are seldom important factors. Static models divide further into such categories as complete and partial; large and small; and low subsonic, high subsonic, and supersonic. Partial models include power plant models, duct inlet and internal flow models, two-dimensional models, reflection plane semi-models, and other component models. (See Figure 1.)

Dynamic models are less common than static models, and, in many cases, require special tunnels. With some exceptions, model weight, moment of inertia, and tunnel speed have to be properly matched to the model scale, with the tunnel density also considered. As a rule, these models more or less 'fly' themselves in the tunnel. Data is obtained by motion picture cameras and by other means. Included in this category are dynamic stability models, free spin models, flutter models, and models of stores or crew which are jettisoned from a complete model. (See Figure 2.)

1.5 Urgency for Model Delivery

A wind tunnel model is a small prototype airplane. In the development of a new design, after the tentative configuration is set, the wind tunnel model must be designed, constructed, and tested with satisfactory results before the project as a whole can be carried to conclusion. Clearly, then, the pressure brought to bear on the model group for the most rapid delivery possible is very great. This factor must be taken into consideration at all times in wind tunnel model work.

2. ORGANIZATION

2.1 Overall Organization

A very efficient organization is needed to manufacture these small prototype airplanes. It is the practice of North American Aviation, Inc., to have this organization all in one group. The main plant at Los Angeles, California, and the plants at Downey, California, and Columbus, Ohio, each have a separate one-group organization.

At the main plant, the Wind Tunnel Model Group is, more or less, a small, independent factory within the main factory. It has its own shop, its own design unit, its own structures unit, its own time-accounting and scheduling unit, and its own administration. The Aerodynamics, Thermodynamics, Wind Tunnel, and Vibration and Flutter Groups are the 'customers.' The objective at all times is to give the 'customers' the maximum possible service; and the relationship between the group and a 'customer' is an important one. It is up to the 'customer' to set up the specifications and standards for the models. The model group will be what the 'customers' demand. Any successful model group owes its success, at least in part, to the groups for whom it builds the models.

A model group should have an overall manager, with a supervisor to head the design unit, and one to head the shop. As in any other manufacturing unit, these supervisors are the key men, and the ones upon whom the success of the organization depends.

There should be very close coordination between the shop and the design group. While a design is in progress, key men from the shop should be called in to go over the drawings while they are still on the board, to be sure that the design will permit rapid and economical manufacture, and that it is adaptable to the particular methods of the shop. Also, while the parts are being made, the designer should visit the shop from time to time to give added information, if needed, and to note what difficulties the shop is having with the design, so that future designs can be improved. To make such close coordination possible, the design group and the shop should be located as close to each other as possible.

2.2 Model Design

Aside from its supervisor, the model design unit should consist of a group of designers, a structures division, and clerks as necessary.

Superior designers with speed and accuracy are required. Slow or inaccurate men can not be tolerated. The difficulty and the scope of problems faced call for men of great ingenuity and versatility. (The North American Aviation Model Design Group has designed items ranging from models with wing panels no bigger than a thumbnail to a supersonic wind tunnel variable nozzle over 50 ft long, weighing over 1,000,000 lbs.)

Strangely enough, experienced aircraft designers have not, in general, worked out very well in model work. The best men have been mechanical engineers or architects. Supplementary training in aerodynamics, shop, and wind tunnel testing is desirable. In model stress analysis work, experienced aircraft structures men have been very satisfactory. Certainly, however, outstanding men are required in both the design and the structures groups.

2.3 Model Shop

The model shop organization should be like that of any other shop, with an overall supervisor, and with assistants and clerks as required. As a rule, there should be a metal division and a wood division. To expedite model delivery, and also to make the most of available equipment, two or more shifts are normally required. Because of the nature of the work, however, additional shifts should be used with caution and should be kept to a minimum.

It has been found that experimental machinists usually work out well in the metal division. Tool and die makers have been less satisfactory. The men should be expert at layout, contouring, and machining. For the wood division, experienced pattern makers have, as a rule, been initially best.

3. THE MODEL SHOP FACILITY

3.1 Building

The model shop should be adequate in size, and as clean and quiet as possible. Lighting should be uniform, with not less than 90 candle power maintained. To avoid shrinkage in the wood used in both models and patterns, the shop should be air conditioned. Air conditioning also improves the efficiency of the personnel in the shop. The area containing the woodworking machines should be partitioned off to prevent the dust from entering the rest of the shop. These machines require the usual dust evacuator system. A special dust-free area should be provided for the construction of delicate high-precision equipment. A welding booth and a paint booth are also required.

In model building, instead of having a man assigned to each machine tool, with many men working on a part, one man constructs a part, using various machine tools as required. This system is considered best for such high-precision experimental work. It does, however, require more space. Average overall space required per model builder should be about 400 square feet.

3.2 Equipment

Equipment should be adequate so that the model-building program will not be delayed.

For the metal division, the usual equipment for a high-precision machine shop is required. The following are some examples of the equipment used:-

1. Precision engine lathe with a profiling attachment
2. Jewelers lathe
3. Universal angle head milling machine with profiling attachment
4. Planer with contouring attachment
5. Shaper
6. Radial drill
7. Jig borer
8. Contouring band saw
9. Surface grinder
10. Tool grinder
11. Large surface plate
12. Granite surface plate
13. Heat treat oven.

For parts, particularly for wing panels which are too large for milling machines, there are contouring machines made especially for wind tunnel model work. These machines can be used either on wood or metal. (The Whaley Engineering Corporation, Norfolk, Virginia, supplies machines of this type. Some other sources for such equipment are the Aerolab Corporation, Pasadena, California, and Contour Company, Rosemead, California. Both of these companies also build tunnel models.)

The following are examples of equipment for the wood division:-

1. Planer
2. Jointer
3. Band saw
4. Table saw
5. Cut-off saw
6. Lathe
7. Sander.

4. INITIAL INFORMATION

4.1 General Information

One of the most important things in model design is, at the very beginning of the project, to obtain in as complete a form as possible, data and specifications on the model and the tunnel it is to be tested in. This is not always possible, but when it can be done, the project proceeds much faster and more smoothly. In general, the responsibility for supplying such information lies with the 'customer.' This matter is of sufficient importance to merit further elaboration.

The subject can be divided into three parts: a general statement, data on the wind tunnel to be used, and data and specifications for the model. The general statement should note the type of model to be built and the tunnel to be used. It should also explain in reasonable detail the purpose and objectives of the test. Furthermore, the urgency of the project and the reason for this urgency in the overall picture should be noted. People work better and faster if these facts are known.

4.2 The Wind Tunnel

Some wind tunnels publish considerable information on the test section, model mounting, etc., and even detailed specifications for the model. This information should always be used when available. On the other hand, sometimes enough information is not immediately available. For this reason, some of the data items needed are listed below:-

(1) An overall description of the tunnel should be given.

(2) For the test section: dimensions, size and location of windows, information on access doors and hatches, lighting, detail drawings, data concerning the walls, and any other information which might be of value.

(3) For the model support: detailed description and drawings, ranges for angle of attack and yaw, position with respect to the test section, load capacity, deflection under load, data on provisions for electrical leads and pressure tubes, and other pertinent information. (Included, of course, should be the same information on available alternate support systems.)

(4) For systems which use the sting-type model support: complete drawings and data on the available stings, including load capacity as well as deflection under load, and provisions for positioning the model in yaw.

(5) For available internal balances: complete data and drawings, including load rating, deflection under load, accuracy, interaction characteristics, lead wire arrangement, effect of temperature, data on the force measuring system, and any other pertinent information.

(6) For an external balance (if used): information essentially the same as for the internal balances.

(7) Complete data and drawings on available force and other calibration equipment should be given.

(8) General assembly drawings and diagrams should be supplied to clearly show the overall tunnel arrangement. In addition, cutaway perspective drawings and photographs should be supplied for further illustration.

(9) Regarding operating conditions, the following data should be supplied:

(a) Velocity range.
(b) Dynamic and static pressures and their ranges.
(c) Temperature ranges.
(d) Velocity and pressure surveys.

(These data are useful in determining the best location in the tunnel for the model and also in evaluating the suitability of the tunnel for the proposed tests.)

(e) Thickness of the wall boundary layer.

(10) For supersonic tunnels, information is needed for various speeds on the test rhombus size, permissible model length and cross-sectional or blocking area, starting and stopping loads, shock wave, and other characteristics. Also data for the schlieren system should be supplied. For intermittent tunnels, running time data should be given.

(11) In regard to pressure instrumentation, data should be supplied on available electric pressure pick-ups, manometers, recommended pressure tube sizes, etc.

(12) Criteria should be set up for model strength. This should include the required factor of safety, and detailed specifications for the stress analysis report, if one is required. Also probable tunnel damage in case of model failure should be noted.

(13) Information should be furnished on available electrical equipment. Included should be information on potentiometers for strain gage force measurement; oscilloscopes and oscillographs; direct, alternating, high-frequency, and variable-frequency current power supply; and other equipment and instruments.

(14) Information should be supplied on model service and model handling facilities. This should include specifications for hoist attachments, if required.

(15) Data should be supplied on the available photographic equipment. For dynamic model testing, information on motion picture camera equipment is particularly necessary.

It should be noted that this is only a partial list of information required in regard to the wind tunnel. As a rule, additional information will be needed, depending on the model to be tested.

4.3 The Model

Specifications should be set up which describe the proposed model in as much detail as possible. The specifications should not, however, be so rigid as to prevent the use of the most appropriate type of construction. Some of the information required is as follows:-

(1) General overall description of the model.

(2) The model scale factor. (As a rule, the model is made as large as will fit properly in the tunnel.)

(3) Schedule of removable parts, off blocks, alternate configurations, etc.

(4) Schedule of angle setting for control surfaces and other parts.

(5) Schedule of control surfaces and other parts which are to have remote control and position indication.

(6) Schedule of model loads to be measured (overall, component, hinge moment, etc.). Also, requirements for calibration and check loading.

(7) Schedule of pressures to be measured.

(8) Suggested type of construction, and other features desired.

(9) Installation and mounting requirements. Position of model in the tunnel. Ranges for angle of pitch and yaw.

(10) Tentative test running schedule.

(11) Complete master dimensions, and lines and contour data to define fully the model, its control surfaces, off blocks, and alternates. (Often these data are not available at the start of a project. In this case, the model design group may have to aid in developing the data.)

(12) Complete information regarding aerodynamic loads on the model and its components. [If an external balance is to be used, overall loads with respect to it should be given to ensure that its capacity will not be exceeded. Other loads should be given with respect to the model, both overall and separate. Although the dynamic pressure of the test should be given, it is preferable to have actual loads on the model or component rather than aerodynamic coefficients. Also, in general, it is preferable to have the loads with respect to the model - that is, normal force rather than lift, and chord force rather than drag. Furthermore, it is preferable to have the position of the load (the center of pressure), rather than a moment. Otherwise, the model designer will have to convert the data into this form for his own use. For airfoils, load data should be given for the exposed part, as well as for the unit as a whole. In some

cases, profile pressure data may be needed. For control surfaces, load and hinge moment data should be given. Load data should be given for all conditions which may be critical in regard to the structure of the model. The design factor of safety should also be given. Load data should be given for those parts which are to have provisions for force measurement in the model.]

(13) Data on permissible deflections of the model and its components under load.

(14) Specifications for model tolerances.

(15) Specifications on accuracy and sensitivity for force and other measurements.

(16) Special models require special information. Dynamic models require data on weight and moment of inertia, mounting, and other factors. Flutter models also require this information, plus elasticity requirements.

5. MODEL DESIGN CONSIDERATIONS

Model design procedure is, in general, similar to that of any other engineering organization. The area should be adequate, well lighted, quiet, clean, with proper heating and ventilation, and should be located close to the shop. A manual should be prepared to guide the designers in their work. Another manual should be prepared for the structures unit.

Because of the urgency for the model, the keynote in model design is to get the drawings to the shop as fast as possible. As soon as anything significant is on the paper, a preliminary print should be released to the shop, so that actual construction can be started.

Drawings should be simple, clear, and concise, but yet should contain enough information to permit construction. The better the shop, the less the detail required on the drawing. It should be realized that the drawing is for a single part, not for a production item. Drawings for an outside shop, of course, have to have more detail.

The usual procedure is to begin with a drawing of the installation of the model in the tunnel. This is followed by general assembly drawings of the model and its major components, such as the fuselage, wing, empennage, nacelles, etc. Details are usually shown on the same sheet. For the smaller models, the entire design, assembly, and details can be put on one sheet. Although it often results in very long drawings, this system keeps to a minimum the total number of drawings for a project. Using one drawing saves time and also reduces the volume of the drawing files.

Drawings normally are of actual size. Very small parts are sometimes drawn twice actual size or larger. Very large parts are drawn half-size or smaller. Drawings should be accurate, but not so excessively precise that they take too long to prepare. (This applies to the picture, which, as a rule, is not used directly for the construction.) Dimensions must be exact.

An airfoil is usually defined by a dimensioned plan form, together with root and tip section coordinates. Generally, the same drawing can be used to define the structure.

For bodies of more complicated contour, such as fuselages, nacelles, or ducting, it is often desirable to furnish separate lines and contour information, so as not to complicate the structure drawing. This information may consist of photographic reductions of the actual full scale airplane loft lines. The reductions may be on galvanized steel sheets so that the shop can use them to make the model templates. This method has a fundamental advantage in that, with it, there is a tendency for the resulting model to represent more faithfully the actual airplane. Deviations in lines built into the airplane will automatically be built into the model. This, of course, is desirable since the model is supposed to represent the actual airplane.

Quite frequently, at the time the model is built, full scale lines are not yet available. In this case, lines have to be lofted especially for the model. When this is done, except for very large models, the lines should be lofted twice size or more, and then reduced to model scale by the photographic method. Lofting by the usual procedure is not sufficiently accurate to be used directly for model work, and the model will not fair properly from station to station.

There is an exception. Lofting, at least in part, can be done by the model shop template department, because their methods and equipment are more accurate. With the use of height gages, etc., and with the lines scribed on the metal template stock, the work, as a rule, can be done directly to scale. A typical example would be the construction of a cross section for a body such as a fuselage. In this case, all that is required are coordinates for the top, bottom, side, and shoulder points. These coordinates are put on the template stock while second degree curves are laid out between the points to complete the section.*

Model drawings should always contain basic reference lines. Drawings of airfoils should show the mean aerodynamic chord. Area and other basic information is also useful.

At all times, consideration should be given to ease of manufacture and to rapid configuration change. A minimum number of screws consistent with strength requirements should be used for attaching parts. For example, a bracket should usually be secured with one screw and two dowels, rather than with two screws and two dowels. Use of very small screws, below number sixes, should be avoided if possible.

Model tolerances are of two types - those that relate to the airplane, and those concerning only the model itself. For those relating to the airplane, including those for contours, overall dimensions, etc., the model tolerance should not be more than the corresponding full scale airplane tolerance multiplied by the scale factor. For example, if the scale factor is 0.10 and the tolerance for a given dimension of the airplane is 0.050 in. the tolerance for the corresponding dimension on the model should be less than 0.0C5 in. Curves should be smooth and free from irregularities.

Tolerances concerning only the model should be appropriate for the purpose (to ensure a good fit, interchangeability, etc.). Close tolerances should be specified only when needed. Otherwise, valuable time in the shop will be lost in making things

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*The method of the graphical construction of the second degree curve and other information useful in aircraft or wind tunnel model line and dimension work is given in Reference 2 by Roy A. Liming, Head of the Engineering Loft Mathematics Group at North American Aviation, Inc.

more accurate than necessary. In general, surface finishes are not specified on model drawings. The shop will, as a rule, put mirror-like finishes on the models.

Model drawings should contain specifications for leveling holes and reference lines to be incorporated in the model. For models which have force-measuring provisions, attachments for calibration equipment should be specified. Also, if special equipment is required, its design should be included as a part of the project.

6. STRUCTURAL CONSIDERATIONS

6.1 General

Supersonic aviation has presented challenging problems to the model structures engineer. The wind tunnels for supersonic testing impose much higher loads on the model, while wings and other parts are thinner. The models require complicated internal balances, which must have a very high load capacity in relation to their size. Airplanes with thinner wings increase the need for flutter model research and also add to the problems of the model stress group.

Stress analysis procedure for a model is essentially the same as for an airplane. There are differences, of course, because of the difference in the type of construction, and the fact that in the normal models, weight is not a predominant consideration.

6.2 Factor of Safety

For models, the design factor of safety - that is, the ratio of the load which would cause failure to the maximum applied load - is usually much higher than that for an airplane. For supersonic models this factor is usually 5, while for airplanes it is 1.5. Some of the reasons for the use of a relatively high factor in models are as follows:-

(i) In the airplane, the safety factor, if not limited, would result in excessive weight which could not be tolerated. In a normal model, weight is not a critical factor.

(ii) The high factor provides a contingency to take care of such things as variation in the strength properties of the materials used, as compared to those predicted, and variations in the actual aerodynamic loads, as compared to those predicted. Before a model has been tested, aerodynamic loads for it are usually not as well known as those for the airplane. (In fact, one of the purposes of model testing is to determine these loads).

(iii) The high factor provides a contingency to take care of limited inaccuracies in the stress analysis and in the method of analysis. This margin, in many cases, will permit the use of a more simplified analysis.

(iv) The high factor ensures against a 'catastrophic' type of model failure. This term is used principally in connection with the common closed-circuit type of wind tunnel, where, in failure, the model or a part of it could be carried downstream to wreck the main drive fan or compressor. Such an accident could result in damage which might require millions of dollars to repair, and which might put the tunnel out of action for many months. Most tunnels of the closed-circuit type have some sort of screen downstream of the test section to catch the model and prevent it from entering the compressor, or at least to break the model into parts so small that they could not cause serious damage. Such screens, however, are of doubtful value. If they are heavy enough to serve their purpose, their resistance may seriously impair the efficiency of the tunnel. Therefore, it is not hard to understand why operators of such tunnels insist upon a high factor of safety.

(v) In a high-speed or supersonic wind tunnel, it is possible for a model or a component of a model to develop a condition of dynamic instability from buffet, vibration, or flutter. This condition can become severe enough to cause a failure. The pulsating loads resulting from this condition are called dynamic loads. They add to the existing aerodynamic loads, and they are, as a rule, extremely difficult, if not impossible, to predict. To provide a contingency for them is a reason for having a high factor of safety. It is known that in general, the stiffer the model, the less likely it is to shake. Also the higher the factor of safety used, the stiffer the model. As a rule, use of a factor of safety of 5 will result in a model which will not develop a severe condition of dynamic instability.

(vi) For some supersonic wind tunnels, starting and stopping loads present a problem. In a closed-circuit type of tunnel, where the overall pressure can be reduced for starting and stopping, the problem may not be critical. These tunnels, however, usually have the 'catastrophic' model failure problem. In the open-circuit, non-return type of tunnel, model failure will usually not result in serious damage to the tunnel. Since means are not available for reducing the pressure, however, starting and stopping loads may become a problem.

These loads, presumably, are caused by the shock wave passing over the model. Also, in starting, until supersonic flow is established, the supersonic nozzle acts as a subsonic diffuser; but the shape, particularly for a short nozzle, is not that of an efficient diffuser. The result is turbulent flow, which imposes violent loads on the model. With a longer nozzle, the shape as a diffuser is better, and starting loads should be less violent. Also, other things being equal, starting loads would be expected to become more severe with an increase in the speed of operation. In a continuous tunnel, with a nozzle that can be adjusted during the run, starting and stopping would be at the lower speeds.

The angle of attack of the model is believed to have some influence on starting and stopping loads. It is generally considered desirable to have it so arranged that the model can be put into the zero angle of attack position for starting and stopping. The advantage of this may not be as great in a tunnel with a short nozzle as it would be in a tunnel with a long one.

While the stimulation may be aerodynamic, dynamic considerations appear to have profound influence on starting loads. In general, the more rigid the model support and the quicker the start, the less the starting loads will be. Also, as a rule, starting loads are capricious and very hard to predict or even measure.

In tunnels where starting loads are a problem, a high factor of safety is used both to provide a contingency for the uncertain starting loads and to provide a more rigid installation in which such starting loads will be lower. While this statement should be considered with discretion, it can be said that, in general, the use of a factor of safety of 5 is satisfactory to take care of starting load problems.

The reasons supporting the use of a relatively high factor of safety in model construction have been presented in some detail because this matter is sometimes not too well understood, particularly by airplane engineers who are accustomed to using a 1.5 factor of safety. To make models strong, obviously, is expensive and takes more time.

6.3 The High Load Problem

It has already been noted that, with modern supersonic wind tunnels, the load imposed upon the model is quite high. From the aerodynamic standpoint, this is desirable because it means that the Reynolds number also will be relatively high. From the structural standpoint, it presents a problem. In some cases, a safety factor of 5 cannot be obtained. In a closed-circuit type of wind tunnel with a pressure control, the pressure can be reduced until the factor is met. This of course, is at the expense of Reynolds number, but it is probably desirable in this type of tunnel, since model failure might be catastrophic.

Consider, however, an open-circuit, atmospherical discharge, supersonic wind tunnel of the type in which the pressure cannot be reduced below that established by the discharge pressure. The minimum operating dynamic pressure would be about 1250 lb/ft^2. With pressure this high, there will be many cases where a safety factor of 5 cannot be obtained. In such cases, it appears that there is no choice but to take the risk of running the model with a reduced factor of safety.

Just how much risk is involved in a given case is difficult to determine, but usually there is some risk even when a high factor of safety is used. In tunnels of this type, model failure might not be catastrophic unless the loss of the model itself would be so considered; on the other hand, starting and stopping loads might be a problem. Furthermore, with a reduced factor of safety, the tendency for dynamic instability is increased.

To illustrate this structural problem, consider a typical airfoil. Take an aspect ratio of 3.5, a taper ratio of 0.3, and zero sweep. Assume a maximum normal force coefficient of 1.2, a dynamic pressure of 1250 lb/ft^2, and uniform load distribution. Assume a fuselage with a width equal to 16.2% of the span. Assume a bending modulus of rupture for 75S-T aluminum alloy of 110,000 $lb/in.^2$ and 285,000 $lb/in.^2$ for heat-treated alloy steel. Assume a solid, full, one-piece wing, or a wing with panels secured to the fuselage by means of a full flange type of joint. (This is the most favorable condition possible). Consider the critical section as that where the wing enters the fuselage. Assume that the maximum applied unit stress is an inverse function of the thickness ratio squared.

For an aluminum alloy wing with an aspect ratio of 3.5 and a factor of safety of 5, the minimum thickness ratio which could be used would be close to 5.19%; for a factor of 3, it would be 4.02%; and for a factor of 1.5, it would be 2.84%. For an alloy steel wing with a factor of 5, the minimum thickness ratio would be 3.22%; for a factor of 3, it would be 2.49%; and for a factor of 1.5, it would be 1.76%. If the aspect ratio were 5 instead of 3.5, other things being equal, the minimum thickness would have to be increased by about 36.8%. With an aspect ratio of 2, it could be as low as 67.8% as thick.

In this illustration, an ideal wing-to-fuselage connection was assumed. Often it is not feasible to realize this. With the conventional rectangular tongue type of joint (with the tongue within the extended airfoil contour, and 50% of the wing chord at the junction), the minimum thickness would have to be increased by about 58%, other things being equal.

This example illustrates the nature of some of the problems the model designer has to face. It shows why, for some wind tunnels, it is sometimes necessary to design for a reduced factor of safety.

Under such conditions, of course, the stress analysis must be more thorough and precise. Uncertainty in regard to the applied aerodynamic loads can be reduced by the use of force-measuring devices built into the model. Starting and stopping loads may present a problem which may be the determining factor. For some installations, however, starting and stopping loads may not be as great as those at maximum lift. In this case, they would not be critical if the model were designed to maximum lift.

6.4 Dynamic Instability

There remains the problem of dynamic instability caused by buffet, vibration, or flutter, or combinations of these factors. The problem may develop in any wind tunnel operation, even when the factor of safety is high, and the dynamic pressure is relatively low. Dynamic instability is difficult to predict. It may occur at one speed and disappear at a higher speed. It has to do with the mass and stiffness characteristics of the model and its installation, the natural frequencies of oscillation involved, and the aerodynamic loads imposed on the model with pulsations in these loads from buffet, shock waves, turbulence, flow breakdown, or some other factor in the tunnel flow or in the model itself. If the exciting frequency is resonant with a model natural frequency, serious difficulty may develop.

The dynamic trouble frequently develops as stall is approached, at which time violent oscillations in pitch may occur. If the wing tends to stall alternately from side to side, a severe dynamic rolling moment will be imposed on the model.

In general, the solution to the problem is to make the model and its installation as stiff as possible in relation to the air loads to be imposed. This implies the use of a high factor of safety, which, as noted, is not always possible. If the performance in this respect could be predicted, it would be of great help; but the difficulty involved has already been explained. In the future, perhaps, specialists will be required for this very purpose. In actual tests, however, the danger involved can often be greatly reduced by careful procedure at the beginning of the program. If the model has an internal balance and other force-measuring devices of the electrical type, these can be connected to oscilloscopes, so that a dynamic loading condition can be detected at the onset. The test is started with the model in the zero angle of attack position, and, if possible, at reduced pressure. As the test proceeds, angle of attack and then pressure are gradually increased, or, if pressure control is not available, only angle of attack is increased. The oscilloscopes should be watched carefully. If a dynamic loading condition of sufficient severity to indicate danger develops, or if design loads are exceeded, the test can be discontinued. By this procedure, it should be possible to detect a dangerous dynamic condition and back away from it before a serious accident occurs. This, then, should tend to reduce the risk involved and perhaps make it possible to use a lower factor of safety in the design.

The problem of fatigue failure has so far not been a serious factor in model work. With the use of higher stress, and with more frequent occurrence of dynamic loads, this problem may develop.

6.5 Proof Loading

When a structure is of such a nature as to make stress analysis extremely complicated or of doubtful value, or if the structure is considered adequate but this cannot be shown by analysis, it is usual to establish its strength by proof loading. The expected load times a factor is applied to the structure and taken away from it. If no permanent set or damage results, the structure is considered satisfactory. If the loading is proper, this method should be more reliable than analysis, since it eliminates the consequences of error in calculation, method, or assumptions. Also, it proves the strength of the particular material used in the part tested.

Some testing agencies specify a general factor of 3 for proof loading, with the exception that if, during the wind tunnel test, the load can be measured, a factor of 2 is permitted. It would appear logical that if it is permissible to reduce the proof loading factor in cases where the operating load can be measured, it would also, for such cases, be permissible to reduce the factor of safety for the stress analysis by a corresponding amount.

It should be noted that a model will have the same structural problems regardless of its size. That is to say, for a given dynamic pressure and for a given condition, other things also being equal, a small model will have the same unit stresses and the same relative deflections as a large one. This does not apply to dynamic characteristics.

6.6 Aeroelastic Models

From air loads and from accelerations of its mass, an airplane structure will have considerable deflection. The wing, particularly a thin, swept wing, will have significant deflection in torsion. The wind tunnel model for the airplane being, as a rule, relatively stiffer, will not have corresponding deflections. The model, then, will not faithfully represent the airplane for the condition in question. The aerodynamicist can generally make satisfactory corrections to take this into account.

When, for a given condition, it is desirable to have the model more accurately represent the airplane, the appropriate deflections are built in. Deflections, both for the airplane and for the model are determined, and the necessary corrections are built into the model. Such a model is called an 'aeroelastic model.' These models are considerably more costly to construct and, while correct for one condition, may not be for another.

Another type of aeroelastic model is one which, under the air load, will have the same relative deflection as that of a full scale airplane. Such a model is not as stiff as a normal model, nor does it have such a high factor of safety. Designing this type of model presents quite a problem. The wing construction is more nearly like that of the airplane, except that glass laminate material is generally used. A model of this type may become a flutter model, whether such a feature is desired or not. The advantage of using this system is that the model will automatically be more accurate over a wide range of conditions.

7. MODEL CONSTRUCTION

7.1 Methods of Construction

Depending on the purpose of the test, the complexity of the model itself, and many other factors, an extremely wide variety in types of construction is encountered in wind tunnel model work. Some of the more or less special factors will be discussed later. Some typical procedures for construction of parts of normal models or patterns will be explained below in simplified form.

The first step is the construction of the templates. If photographic template lines are not available, the layout is made in the shop, using a surface plate, height gages, and angle blocks. For the more accurate templates, the material used is 1/32 in. thick steel template stock. The shape is cut out roughly on a metal band saw and then filed accurately to contour.

In the next step, two or three basic reference planes are faced off on the rough material, which may be either metal or wood. The template stations and other required lines are then laid out on these planes.

Next, the material is removed, and the templates are fitted into place with the contour faired between them. This is done in a gradual manner, with the body first being put into a rough form and finally worked into the finished form. For a metal part, the material is removed by machine tools, and the final contour is worked by hand filing. For wood, chisels and other woodworking tools are used.

For relatively thin parts, such as airfoils, warping is a very troublesome problem. The material has to be removed gradually from side to side to keep warping to a minimum. As the material warps, reference planes and template stations have to be shifted and relocated. (This is one explanation of why models cannot be constructed as rapidly as some people think they should.)

In the final stage, the part is sanded and polished. When the material is wood, the sanding sealer is applied in this stage. It is not the usual practice of North American Aviation, Inc., to use any other finish for wood models. Lacquer surfaces tend to crack. Color covers up reference lines and screw locations. Heavy coating can build up the surface to destroy its accuracy.

The above procedures, while typical, do not apply in all cases. For metal bodies, with the exception of airfoils, it is more usual to construct a pattern first, and then to do the work in a profiling machine. More about this will be explained later. It is appropriate, now, to examine the general problem in more detail.

In model construction work there are, in general, two basic types of bodies to consider: bodies such as fuselages and nacelles, and airfoils, which include the main wing and the tail surfaces. The fuselage-type body will be discussed first.

7.2 Fuselages

The simple fuselages are made of wood, or, more frequently, of a metal longitudinal spar with wood covering. The wood used is laminated Honduras mahogany, with the grain in the fore-and-aft direction. White holly is also used, particularly on smaller models. It has closer grain structure, but has a greater tendency toward shrinkage. The wood blocks are secured to the spar by screws. The screws should have large washers to prevent excess bearing on the wood. The spar, rectangular in shape, provides anchorage for the wing, the empennage, and perhaps for the model support connection. The material used is either steel or aluminum alloy. (See Figure 3.)

In fuselages which have an internal duct for the engine air flow, a steel tube is used for the structure, with the tube also serving as a duct. The steel tube structure is also used to provide housing for an internal balance. If there is a motor for propeller drive, the steel tube structure is used for support.

The fuselages just described have been excellent for subsonic wind tunnels, but less satisfactory for supersonic testing. In supersonic testing, very dry air is used, and operating temperatures are from 120°F to 150°F. The wood tends to shrink and crack. Also, from dust in the air at such high speeds, there is an abrasive action on the forward surfaces which causes them to become rough. These difficulties can be overcome, to a large extent, by using a coating of glass laminate over the wood surfaces. The thickness of the coating is usually about 1/16 in. First the wood is undercut; then the coating is applied oversize and filed down to contour with the use of the templates. A filler and a lacquer paint are used to provide a smooth finish. Data on the glass laminate construction is given later.

There are cases where, either all or in part, the type of construction just described cannot be used. These are cases where an extra large cavity is required within the body to provide room for an internal duct or balance, some remote control device, or other equipment. Included in this category are the very small supersonic models for which wood construction is not considered feasible. In these cases, either metal or plastic, such as glass laminate, is used.

With metal construction, either a casting is used, or the part is machined from a solid block of material or from a forging. Whether or not a casting is used depends upon the particular circumstance. The castings are, as a rule, either of aluminum alloy or magnesium. Frequently the surface will not be accurate enough, so that the casting will have to be made oversize and contoured anyway. In such a case, a great deal of the advantage of using a casting is lost. In practice, the casting type of construction has proved quite expensive.

In many cases, particularly when more strength is needed, it is advantageous to machine the part from a block of metal or from a forging. For the exterior contour, a profiling machine of one type or another is used. The first step is to make the male pattern. A hard tooling plastic is used. Two methods are used for making the male pattern.

One method is as follows: First a male pattern is carved from wood. Secondly, from the wood pattern, a plastic female mold is made. Glass cloth is used for backing. Before casting, the pattern is waxed, and a parting agent is applied. Third, from the female mold, the hard plastic male pattern used for the contouring is cast.

The second method, more direct, more accurate, and faster, is used where practical. It consists first of constructing a set of male cross-section templates. These templates are mounted in proper position on a plate which has the shape of the fuselage profile. The tooling plastic is then used to fill in the contour as established by the templates.

For small supersonic models, the pantagraph profiling machine is used. The patterns are made double-size. This results in a more accurate model. Such fuselages are usually made of brass.

Internal contours, such as the inside surface of a duct, are much more difficult and time-consuming to build than external ones. A fairly easy method, however, has been developed for making the female pattern required for such contours. First, a male wood pattern is made. Then the female mold is cast around it, using tooling plastic with glass laminate backing. This female mold is then used as the pattern for the contouring.

As a result of the constant effort to find methods to reduce costs and time required for model construction, the use of plastics has been increasing. The application of the material as a coating for wood model parts and for patterns has already been noted. Plastics are also used frequently in place of aluminum alloy or magnesium castings. The strength is comparable, the finished part is accurate, and construction time and cost are much less. In model work, glass fiber is usually the reinforcement.

The following procedure is used for the construction of a simple solid fuselage or similar part: First the core is built up. The core can be made of glass mat filler, wood, such as mahogany or even balsa, or any other suitable material. Then the glass laminate plastic is applied layer by layer. The surface is worked to shape with the templates used to establish the contour. Finally the finish coatings of filler and paint are applied. Metal inserts for attachments or reinforcements, as required, can be cast or incorporated into the structure.

An improved variation of this procedure is as follows: The body is built as described, but left about 1/32 in. undersized. Then a female mold of the outside contour is made. This mold is made by first making a wood male pattern and casting the plastic reinforced fiber glass over it. The mold is then placed over the body, and the plastic is poured in. The resulting part has a smooth finish. The necessity of finish-contouring the hard plastic surface has been eliminated, and considerable time is saved.

An excellent method has been devised for making fuselages or other bodies which are shell-like in construction, with interior cavities. First a wood pattern of the interior shape is made. Then the glass laminate material is cast around it and built up to the approximate outside shape. Next, the external surface is cast on, using the method previously described. Finally, the wood pattern is chopped out to leave the finished part. The resulting interior shape is smooth and accurate.

In addition to constructing such bodies as fuselages, there are, of course, many other applications for plastics. For example, plastics are excellent for fillets and fairings and for reinforcement of thin edges of wood parts. The more highly stressed parts should be designed with care and with proper account taken of the particular strength characteristics of the material.

The material used for model work is a tooling-type epoxy resin. It is thermosetting, dimensionally and chemically stable, and it can be used without the application of heat or pressure. It sets up in about half an hour. This material is harder to work than wood, but easier than metal. Metal-working tools are used. Tools dull rapidly, so carbiloy bits are used.

The North American Aviation, Inc., Model Shop used a material called 'Ren-ite' (supplied by Ren-ite Plastics Inc., Post Office Box 1256, Lansing 4, Michigan, U.S.A.). Different types of the material are used for different purposes. For male patterns, 'Splining Scratch Coat' material is used for build-up, while 'Splining Coat' is used for the surface. For interior surfaces, 'Surface Coat' is used. 'Laminating' resin is used to build up the glass laminate and for casting the exterior coat on models when this type of casting is done. Layers of glass cloth 0.010 in. thick are used for the reinforcement. When the exterior surface is not cast on, glass cloth 0.003 in. thick is used near the surface for greater smoothness.

The following is a list of typical physical properties for a glass laminate construction (Ren-ite # 1130), as published by the Ren-ite Company.*

Specific Gravity	1.57
Rockwell Hardness	M80
Tensile Strength	27,400 lb/in.^{2}
Flexural Strength	19,100 lb/in.^{2}
Compressive Strength	31,500 lb/in.^{2}

The properties depend on the direction of the load with respect to the laminations. This should be taken into account in the design.

7.3 Airfoils

The basic procedure for the construction of airfoils of simple shape is as follows: First, the plan form is laid out on the material. Then airfoil section templates are set up at the root and the tip. Male templates are used whenever possible. If this is not possible, female templates are used to establish section on the actual material. Next, the material is removed along the genatrix lines, that is, along lines of constant chord between the root and tip templates. If the part is metal, it is then filed smooth, sanded, and polished. If the part is wood, it is sanded, and the finish is applied.

If the airfoil is tapered and has constant thickness ratio and no twist, the genatrix lines meet at a point outboard of the tip. This point, then, can be used in place of a tip template.

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*More detailed information on the use of Ren-ite # 1130 can be obtained from its manufacturer.

Metal airfoils are usually made in a milling machine. A special fixture is used to position the part properly with respect to the milling head. Use of this fixture makes it possible to do the work in minimum time. (See Figure 4.)

As already noted, special machines are available for constructing airfoils which are too large for the milling machine. (See Section 3.2.) In this type of machine, the part is clamped to a surface plate. A beam supports a milling fixture, and provision is made for the fixture to travel along the beam. Each end of the beam is adjustable to position the cutter properly with respect to the part. The machine can be used for either wood or metal. In some machines, provisions are made so that for softer materials, a router can be used in place of the milling cutter. (See Figure 5.)

Occasions for construction of the simple wood airfoil have become rare. As a rule, structural considerations, as well as the need for providing suitable anchorage for control surface, flap, or slat brackets, or for mounting, dictate the use of the steel spar with wood covering type of construction. The spar is extended to the tip and buried in the wood, and the wood is glued to the spar.

Epon No. 8 cement, obtained from the Shell Oil Company, is used either for gluing wood to metal or metal to metal. The metal should first be sandblasted. For joining wood to wood, weldwood glue is used. Laminations and grain are in the chordwise direction. Spanwise grain direction should not be used because uneven shrinkage, top to bottom, will warp the spar. The spar may be of steel or aluminum alloy. The usual wood is mahogany. Spanwise strips of holly are used to reinforce leading and trailing edges.

The metal spar with wood airfoil construction is generally satisfactory for relatively thick airfoils where structural problems are not too severe, and where erosion or shrinkage difficulties are not encountered. When these problems are encountered, or if the airfoil becomes too thin for wood, metal construction is used. Difficulty in regard to dimensional stability has been experienced with the metal spar and wood airfoil construction if the thickness ratio is below about 7%.

The material used for metal wings is usually aluminum alloy. In using this material, serious warpage trouble may develop. This trouble can be greatly reduced by the use of pre-stretched material. The material should be double-stretched, that is, stretched in both the lengthwise and crosswise directions.

For thinner airfoils, aluminum alloy may not be strong enough. In this case, high-strength alloy steel is used. A material well suited to this purpose and to model work in general where high strength is needed, is Armco 17-4 PH precipitation hardening stainless steel, supplied by Armco Corporation of Middletown, Ohio, U.S.A. The principal advantage of this material is that it can be machined to finished dimensions in its annealed state. The material is hardened by an aging process which consists of heating it to $850^{\circ}F$ for an hour and then allowing it to cool. During this process, no scaling and very little distortion or dimensional change occurs; the resulting material is very stable. This material is also stainless, and it is magnetic, so that it can be secured in a magnetic holder. In the hardened state, it has an ultimate tensile stress of about 200,000 $lb/in.^2$ and a yield stress of about 180,000 $lb/in.^2$

For attaching the airfoil panel to the fuselage, use of a rectangular tongue extending from the root of the panel into the fuselage is a simple, economical method. For ease of manufacture, this tongue should be within the extended airfoil contour. In some cases, it is not feasible to use this method. Sometimes a rectangular socket is milled into the wing root section. Then a tongue extends from the fuselage into it. Another method is to use a fork-shaped bracket in a recessed area provided in the root region of the airfoil. The airfoil contour is then filled in over the area occupied by the fork with some material, such as a plastic. For maximum strength, either an extra large tongue or a flange type joint is used. (See Figure 6.)

Flaps of the slotted type are secured to the wing panel by means of simple bar type brackets, a pair of them for each part. Sets of brackets are then provided for each position setting.

Wherever feasible, control surfaces are supported by hinge brackets. Angle setting is through the use of a shaft with index pins. The brackets, the shaft, the part into which the shaft fits, and the pins should be of high-strength alloy steel. Taper pins should be used if possible. This method is desirable because it permits rapid changes while the model is in the tunnel, and accurate repeatable settings. Sometimes this method is not feasible, either for structural reasons or because the hinge line is too close to the surface to permit the use of an adequate sized shaft for indexing; in such cases, the surface is mounted with hinge brackets, but a bar type bracket is used to hold the angle position, with a different bracket for each setting.

Horizontal tail surfaces are mounted to the fuselage with provision for angle setting. The preferred method is to provide a hinge mounting for the surface, with angle setting established through the use of index pins. These pins may engage in a sector or a cylindrical segment. Where required, the pins have a threaded hole to permit attachment of a tool so that they can be pulled out for a setting change.

8. MODEL MECHANISMS

8.1 The Problems

Various types of models employ different types of mechanisms. The discussion here will be confined to those mechanisms used in normal models for the remotely controlled operation and remote position indication of control surfaces or other parts.

In large, powerful, continuous, supersonic wind tunnels, occupancy time is extremely expensive. Maximum advantage must be taken of the time available. Requirements for shut-down for model change must be kept to a minimum. In the very powerful tunnels, shut-down for model change may take over an hour and represent a cost of several thousand dollars. It can easily be seen why means for changing the angle setting of a control surface without stopping the tunnel operation is most desirable. The extra cost for such a mechanism will be justified, although the model construction period may be extended.

On the other hand, with modern aerodynamic shapes, the problem is extremely difficult, since the wings and tail surfaces are very thin. The fuselage is filled up with an internal balance and, perhaps, an internal duct. Little space remains for a mechanism.

Need for hinge moment measurement on the surface to be operated further complicates the problem. If the problem can be solved at all, it will require great ingenuity on the part of the designer.

8.2 The Drive Mechanism

The usual method for moving a part is by use of a small electric motor with an irreversible reduction gear drive. The gearing is either directly connected to the part, or it is connected to it through a crank and push rod system. The gear system, of course, must be completely free of play.

Another system which has been used when space is available, is a mechanism which automatically inserts and withdraws, in progression, index pins in a segment of a cylinder. Each pin is joined by a connecting rod to a common motor-driven crankshaft, much like the arrangement of the pistons in a gasoline engine. The advantage of this system is that it permits discreet repeatable angle settings. (See Figure 7.)

A limit switch system is usually required to protect the equipment. If a crank and push rod system is used with the arrangement, so that the crank can rotate through a full revolution, the limit switch system can be eliminated.

Small drive motors with reduction gearing are available. One such motor used in model work is the Globe MMA-57 d.c. motor supplied by the Globe Industries, Dayton, Ohio, U.S.A. It is 1.25 in. in diameter by about 4 in. long, and has a speed of 0.87 r.p.m. a torque of 62.5 in. lb, and a reduction gear ratio of 21,808 to 1.

When space is not available for mechanisms such as the ones described, different and more compact systems will have to be developed. Just what these will be is hard to predict. Perhaps some trigger release system will be used in which, possibly, the air load on the surface will provide the moving force.

8.3 Position Indication Mechanism

Various systems for the remote indication of the position or angle setting of the part may be used. When space is limited, a potentiometer, differential transformer, or some other miniature electrical position pick-up can be used. The output of these pick-ups is usually calibrated against known angle positions.

When space is available, the Selsyn system for position indication is suitable. Three types of Selsyn systems are described:-

The first system is perhaps the most accurate and dependable, but it also takes the most space. Two sets of Selsyns are used, one for fine reading and one for coarse reading. The coarse Selsyn is connected more or less directly to the part and, in any case, the generator revolves through less than one revolution. The fine Selsyn generator is geared up many times with respect to the part. The greater the gear-up, the greater the accuracy of the reading. The gear-up may be constituted by the actuation drive system, or it may be an independent system. Each Selsyn indicator motor has only a lightweight pointer, so that virtually no torque is applied to disturb its accuracy.

The second method is like the first, except that the coarse Selsyn system is eliminated. In its place, the indicator motor is connected to a counter to show how many revolutions it has made; or alternatively, the motor may drive a second (coarse) pointer through reduction gearing. Torque required to drive either the counter or gearing will cause a deviation in the fine pointer but, if the gear ratio is high enough, this deviation is not likely to be significant.

The third method is also similar to the first one, but the gear-up system is eliminated. A large dial and long pointer are used to obtain the desired accuracy of reading. To eliminate errors due to inaccuracies in the Selsyn system, the installation should be calibrated against known angle positions. Systems using the first or second method should always be calibrated if a non-linear drive is used, and it is advisable to calibrate them under any conditions.

One source for small Selsyn (or synchro) equipment is the Clifton Precision Products Company, Inc., Clifton Heights, Pennsylvania, U.S.A. This company supplies a 400-cycle unit, 0.937 in. in diameter by 1.241 in. long. It also supplies a d.c. instrument motor, 0.75 in. in diameter by 1.25 in. long.

9. DYNAMIC MODELS

9.1 General

Watching a normal static wind tunnel model being tested is not much different from seeing the model at any other time, since there is no movement. The test of a dynamic model, on the other hand, is more interesting to watch. Often the impression is given of observing an airplane in actual flight. The motion picture camera is a primary instrument for recording performance.

A test of a free spin model is particularly interesting to observe. A special tunnel with a vertical, upward airstream is used. The model, with its controls set for a spin, is tossed into the tunnel. It goes into a spin. By means of an electromagnetic remote control device, the controls are set for spin recovery. The model then recovers from the spin, if it will recover, and it dives into a net in the bottom of the tunnel. Spin models, with a span of about two feet, are usually made of wood of appropriate density. They are dynamically similar to the airplane and of constant density. In other words, model weight equals the full scale weight times the cube of the scale factor. Since these models are adequately described in tunnel specifications and other places, there is no need for detail here.

The usual dynamic stability model is in general similar to the free spin model, except that it is tested in a wind tunnel which has a sloping airstream. In another type of dynamic stability test, a normal static type model and an ordinary wind tunnel are used. The model moment of inertia is not in proper relation to that of the airplane, but appropriate corrections are made. The model is equipped so that it will pivot about some axis (pitch, yaw, or roll) through the point which represents the airplane center of gravity. Restoring springs are provided. During the test, by means of a remote operating device, the model is positioned out of trim and released. Observation is then made of the oscillation and damping characteristics.

9.2 Jettisonable Models

Jettison tests are for the purpose of determining the path taken by a body released or ejected from an airplane, and in particular for finding out whether or not the body in this path will strike some part of the airplane. A normal, static type model is used in an ordinary wind tunnel. The body tested is the dynamic model. It may represent a crew member, an external store (such as a fuel tank), or any other body to be released from the airplane. The model body must be dynamically similar to the full scale body it represents, weight ratio being determined by dimensional analysis.

Some of the most common tests are those for external fuel tanks mounted below the wing from a pylon. The release mechanism, in its attachment to the tank and its action, should represent the full scale one as closely as possible. Since space available within the wing is limited, a very compact mechanism must be used. A spring-powered device with an electric solenoid-operated trigger release is often used. (See Figure 8.)

Models are constructed to represent the tanks in the full, partly full, and empty conditions, with several of each made to permit a series of tests. As a rule, the empty type of tank has to be very light in construction. Glass laminate construction is used. The method is as follows: The tank is made in halves, cemented together. Each half is moulded on a wood pattern which is undersized by the amount of the skin thickness. Three layers of 0.003 in. thick glass cloth are applied, using the Ren-ite laminating material. Final skin thickness is about 0.020 in. Glass laminate bulkheads are cemented into place. Before the halves are assembled, ballast in form of lead weights is added to give the unit the proper weight and moment of inertia. In a like manner, the same model tank construction can be used to represent a full or partly full tank. Appropriate ballast is added for the condition desired. (See Figure 9.)

The weight and moment of inertia are calculated in the design of the model. For a check, the model is weighed, and the moment of inertia is determined experimentally. To determine the moment of inertia, the model is suspended by a pair of flexible cords of known length, equi-distant from the center of gravity, and is made to oscillate. The frequency of oscillation is measured. With this and the geometry of the installation known, the moment of inertia can be determined.

The tank is usually destroyed in the test. A screen, downstream of the test section, is needed to collect the parts.

For a partially full tank, it is sometimes desirable to determine the sloshing effect of the fuel during the tests. In this case, the lightweight tank is partly filled with a liquid. Finding a safe liquid with the right density may be difficult. Use of actual fuel, of course would, in most cases, be dangerous. Water has been used successfully. To represent a relatively high altitude condition, a liquid somewhat more dense than water may be needed. For this purpose, a mixture of barium sulphate, clay, and water has been used.

9.3 Flutter Models

Flutter models are used to determine flutter characteristics of airplanes. The ordinary type of wind tunnel is used. With respect to the airplane, the flutter model, like other dynamic models, must have dynamic similarity with regard to mass relationships;

but unlike other dynamic models, it also must have dynamic similarity with regard to elastic characteristics.

The core of a flutter model is a metal skeleton upon which are mounted lightweight structural fairing pieces to fill out the external shape. The skeleton consists essentially of a longitudinal structural spar for the fuselage, and one spanwise spar for each wing panel. It is through the proper proportioning of these spars, together with the proper selection of their material, that the desired elastic characteristics are obtained. The spars are usually rectangular in section. The wing spars throughout their length have slots in the center of the top and bottom surfaces. With this shape, the height and width of the spar and slot width are proportioned to give the correct stiffness in the normal (vertical) direction, the chordwise direction, and in torsion. (See Figure 10.)

The fairing segments, both for the fuselage and wing are of hollowed-out wood construction. Either balsa or pine is used. Ballast in the form of lead weights is added to give the segment the correct weight and moment of inertia. To prevent the segments from carrying any load into the spar except their own air load, adjacent segments are separated from each other by a gap about 1/8 in. wide. The gap is then sealed by a thin rubber strip cemented in place. (See Figure 11.)

If flutter characteristics for the empennage are required, the same type of construction is used. Usually, however, empennage characteristics are determined by separate tests. The empennage for the model, then, can be of simple lightweight wood and metal construction with appropriate weight and moment of inertia.

External stores, such as under-wing-mounted fuel tanks, are represented. The object is not to determine flutter data on the tank itself, but to find the effect of the tank on the flutter characteristics of the wing which supports it. Construction of the tanks is very similar to that already described for jettisonable tanks, even to the extent of using a liquid to simulate the partially filled condition. The attachment of the tank to the wing is so designed that, in the event of violent flutter, the store will separate from the wing rather than cause the wing to break.

The model is supported in the tunnel by cables. With the exception of the drag cable, these cables are spring-loaded with springs of low elastic restraint. This gives the model a floating effect. (See Figure 12.)

In the usual test, the speed of the tunnel is gradually increased until flutter occurs, or until a speed well beyond that corresponding to the limiting flight speed of the airplane is reached. Since, in a test of this type, model failure is a possibility, a suitable screen should be provided downstream from the test section to collect any parts which might go down the tunnel in the event of such a failure.

10. DUCT INLET MODELS

The modern supersonic jet airplane presents problems in regard to getting air efficiently into the engine. To help solve these problems, the duct inlet model is constructed and tested. In a model of this type, the inlet and diffuser up to the engine face are represented. At this point, pressure instrumentation is installed to show pressure recovery and distribution, andan electric dynamic type of pressure pick-up is installed in the diffuser for buzz detection. Also, additional pressure instrumentation is installed, as needed, for analysis of the operation of the inlet. From the engine face back, ducting and equipment are supplied for measurement and control of mass flow. Correct external lines are represented to the extent necessary to ensure functioning of the inlet consistent with the design. (See Figure 13.)

An otherwise efficient inlet may have some adverse aerodynamic result, such as excessive drag. It is, therefore, frequently necessary to determine the effect of the inlet on the aerodynamic characteristics of the airplane. This may present quite a complicated problem, the complete solution of which might require that the model represent the complete airplane and be a combined duct inlet and aerodynamic model. (On a model of this type, the inlet might be smaller than desired for duct inlet research).

Another solution is to build a separate duct inlet research model of large scale, and to incorporate the duct inlet on the aerodynamic model only to the extent required for determining aerodynamic effects. For determining aerodynamic effects, the internal duct is required, together with provisions for measurement and control of mass flow; but the diffuser, as such, and instrumentation for measurement of pressure recovery are not needed.

For configurations where the inlet is well forward on the fuselage, a third method, although not a complete solution, may be suitable. In this case, the model consists of two parts: the forward part of the fuselage containing the inlet upon which force is measured, and the aft support part incorporating the equipment for measurement and control of mass flow. Force is measured through the use of a six-component internal balance, which supports the forward part of the fuselage and is supported by the aft structure. The aft structure is mounted on the tunnel support system.

The scale ratio for a model of this type can be considerably greater than that for a complete model; but as a rule it is somewhat less than for a duct inlet model, which does not have the force measurement. The length of the force-measured part of the model should be such that the reflected bow wave at the minimum supersonic speed will not strike the force-measured part of the model. In all cases, accurate mass flow and momentum data at the exit of the force-measured part of the model are necessary for accurate determination of drag.

Internal contouring required for a duct is costly and time-consuming. Many hours are often required for the construction of a duct model. A relatively long duct of metal or wood has to be made in parts to permit access for contouring. Also it may have to be made in three, rather than two, parts. This is so it can be progressively assembled, leaving off one part at a time to allow access, so that the joint connecting the other two parts can be made flush. This is obviously a difficult and expensive type of construction. Wherever possible, the plastic type of construction is used instead. Use of plastic construction eliminates the internal joints and is much quicker. (See Section 7.2).

If the bursting pressure is high, and the lips are thin, and if there is a boundary layer gutter, the forward part of the inlet may have to be of one- or two-piece metal construction, depending upon the structural loads. Progressing back from the inlet, the wall thickness of the duct will usually increase to a point where plastic construction can be used. In some cases, the metal part may be cast with the plastic to form one part.

Tubing for pressure measurement can be cast into the plastic material and can be soldered or cemented in the metal parts. Stainless steel tubing with a 0.049 in. outside diameter and a 0.033 in. inside diameter is generally used. A flexible plastic tubing is used in conjunction with the metal tubing. It has a 0.070 in. outside diameter and a 0.038 in. inside diameter. A suitable tubing is Templex 105, size No. 19, temperature- and oil-resistant plastic tubing, supplied by the Irvington Varnish and Insulator Company, Irvington 11, New Jersey, U.S.A.

In the diffuser, provision is made for the installation of a pressure transducer, that is, an electrical pressure pick-up. The transducer is connected to an oscillograph for buzz detection. The following are some sources for transducers: Consolidated Engineering Corporation, 300 North Sierra Madre Villa, Pasadena 8, California, U.S.A.; and Statham Laboratories Inc., 12401 West Olympic Blvd., Los Angeles 64, California, U.S.A.

At the engine face, the duct is of cylindrical form with the diameter that of the engine inlet. From this point back, the duct is circular in shape, and metal tubular construction is used. The engine accessory cover is represented. It is supported by a cylindrical nacelle, which in turn is supported by radial struts.

The following is a description of a typical installation at the engine face plane for measurement of pressure recovery and distribution: There are a total of 48 tubes used, 12 for static pressure and 36 for total head pressure. Six of the static tubes are located around the accessory cover surface, and six around the diffuser wall. The total head tubes are arranged in six radial rows, with six tubes in each row, and radial spacing such that each tube will sense an equal area. These tubes extend forward from, and are supported by, the six radial struts which support the nacelle. This type of support for a pressure rake is desirable. (A self-supported type of rake has been known to disappear during a test). The part just described, including the accessory cover, the nacelle and supports, and the supporting tube, is called the dummy engine. (See Figure 14.)

From the dummy engine back, the ducting leads into the flowmeter installation. While there are many ways to measure mass flow of air, the North American Aviation thermodynamic engineers prefer the use of a venturi type flowmeter with an A.S.M.E. (American Society of Mechanical Engineers) standard nozzle. Dimensions for this type of installation are given in the A.S.M.E. handbook.

The advantage of a standard flowmeter of this type is that it is very accurate and does not require calibration. It is used, in fact, to calibrate other equipment. As a rule, however, it is not possible to get equipment as large as this within the wind tunnel. The length of the space available may be limited. One limitation, for example, is that the discharge should be in a low-pressure area, ahead of the tunnel shock wave. The preferred solution to the problem is, in this case, to duct the air outside of the tunnel and locate the flowmeter and throttle where adequate space is available. The air is then either ducted back into the tunnel in a low pressure region, or a blower is supplied to pump it through the system.

When an installation of this type is not feasible, a dimensionally condensed flowmeter of the same principle is installed behind the model. This condensed flowmeter must be calibrated. From the dummy engine, a diffuser is used to increase the cross-sectional area as much as possible within the available space. At the end of the diffuser, one or two screens are used to straighten out the flow. These are followed by a cylindrical section of ducting, with a length at least twice its diameter. Next is the nozzle. Its cross-sectional area should be at least 30% greater than the minimum area forward, in order to ensure against choking. The contraction diameter ratio should be at least 1.5 to 1. From the nozzle, another diffuser is used. Its purpose is to provide enough exit area to ensure adequate mass flow, and to space the throttle far enough back from the nozzle so that throttle action will not disturb nozzle accuracy. The throttle is usually a cone or parabolic shaped plug with remotely controlled electric motor actuation.

In models where force measurement is provided, the force-measurement-part body includes the inlet, the diffuser duct, and the dummy engine. It may not include the flowmeter and throttle installation. In this case, a non-force-transmitting connection must be provided between the dummy engine and the flowmeter. A labyrinth type of seal is used for this purpose. A cylindrical sleeve is extended back from the dummy engine. This sleeve is enclosed by the labyrinth seal, which is a cylindrical body with 12 or more internal angular rings.

For a duct diameter of 4 in. the gap between the seal and sleeve should be about 0.005 in. With this gap, the leakage should be about one per cent of the total mass flow for a pressure differential of one atmosphere.

Using such a small gap, provision is required for adjusting the position of the seal in relation to the sleeve it encloses. This may be done as follows: A socket extending from the flowmeter encloses the labyrinth seal with clearance substantially greater than the gap. A rubber seal is provided between the socket and the labyrinth seal. The labyrinth seal is then supported from the socket by radially located screws, through which the adjustment can be made. The labyrinth seal must not contact the sleeve, or force will be transmitted. An electric grounding indicator is provided to ensure against this. (See Figure 15.)

11. MODEL FORCE MEASUREMENT

11.1 Methods of Measurement

This discussion will be confined to force measuring equipment contained within the model. One of the most common means for force sensing is the electric resistance strain gage, the principles of which, it is presumed, are understood. For review, it should be noted that the basic idea is to have the forces to be measured induce strains in certain areas and to apply strain gages to those areas to measure the strains. These measured strains are calibrated against known applied loads. Furthermore, in most cases, there should be provision for temperature compensation. This means the employment of at least two gages, one loaded positively and one negatively. If this is not feasible, then a loaded gage and an unloaded dummy gage should be used.

In the design of equipment of this type, there are some other basic considerations which should be noted. Use of high unit strain for the gages is desirable because it results in high sensitivity and reduces the relative deviation from temperature effects. On the other hand, it means greater deflection. This is not desirable since it might result in greater interaction, permit the part to be displaced further out of position, and increase the possibility of dynamic instability. In practice, some compromise has to be made. The compromise depends upon the particular problem. North American Aviation has used unit strains as low as 0.0001 and as high as 0.0020, although unit strains of about 0.0005 are more usual. For models subjected to high temperature, a high unit strain is used where possible.

The metal most frequently used by North American Aviation for this equipment is Armco 17-4PH steel. The Baldwin AB-11 and AB-19 strain gages are the ones most often used.

Some of the basic elements used for force measurement are the following: First, there is the widely used beam in bending, ideal because one surface will be in tension while the opposite is in compression, thus satisfying the temperature compensation requirement. If used as a cantilever, the beam can be tapered for more uniform strain.

In cases where the stress is direct tension only, or, alternately, direct compression (as in a column or rod) one gage is mounted along the line of stress, while the compensating gage is mounted crosswise (at 90^{o}) to it. In accordance with Poisson's ratio, the compensating gage is stressed about 25% as much as the main gage, and in the opposite sense. With this system, for the same maximum unit strain, the average unit strain (and thus the sensitivity) is only about 60% to 65% as much as that for the beam in bending system. In general, however, deflections will be lower.

For shear, one gage is mounted at 45^{o} to the line of shear in one direction, while the other gage is mounted at 45^{o} to the line of shear in the opposite direction, the two gages being at 90^{o} to each other. In this case, the stress in one gage is equal to that in the other, but it is opposite in direction. This method is used for measuring the torsion in a tube or a bar.

In the measurement of torsion or of direct tension and compression, as already described, a duplicate installation is mounted on the opposite side of the member to cancel out the effects of bending. Accurate placement of the gages is important here, as it is in all strain gage work. In cases where gages are mounted at 90^{o} to each other (as for shear or tension-compression pick-up), the use of the rosette type of gage may be advantageous. In this type of gage, the two grids, 90^{o} apart, are in one unit.

In force instrumentation, pivots of little or no friction are an important item. One of their principal purposes is to enable the loading of a member with the load it is supposed to measure, and no other. This eliminates interaction.

In certain instances, use of the familiar ball bearing and roller is suitable. Miniature ball bearings are sometimes required. Ball bearings as small as 0.100 in. in diameter by 0.031 in. wide, with an 0.025 in. bore, are available. One source of supply is Miniature Precision Bearing Inc., Keene, New Hampshire, U.S.A.

In other cases, use of the flexure pivot* may be dictated. In general, these installations are more rugged, more trouble-free, and have less hysteresis.

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*Information on the flexure pivot is supplied in References 3 and 4.

In model work there is frequent use for a link designed to measure loads in tension or compression. Universal flexure pivots are provided at each end of the link, so that only the load to be measured by the link will be taken. The universal flexure pivot arrangement consists of a pair of flat flexures in succession along the axis of the link, with the planes of the flexure within the axis and at 90^{o} to each other. (See Figure 16.)

Two methods of force pick-up are used: the direct tension-compression system, and the 'race track' system. The direct tension-compression system is used where the load to be transmitted is relatively high (100 lb and over), where space is limited, and where extra-high sensitivity is not required. A simple 'H' section column is used, with the gages mounted on the web. The advantages are ease of manufacture, compactness, high capacity, low deflection, simplicity, and linear calibration characteristics. The 'H' column also is not sensitive to moment or torsion which might be transmitted through the flexures. For lower loads (loads under 100 lb), the 'race track' type of pick-up is used. It is also used for links designed for higher loads when extra-high sensitivity is required.

The 'race track' type of pick-up is a modified form of the ring type. In the loop at each side, there is a straight portion to provide a flat surface upon which to mount the strain gages. Four gages are used, two on the inside and two on the outside. The load is applied to the ends. If the unit is in compression, it will put the inside gages in compression and the outside gages in tension, on the beam-in-bending principle. This 'race track' type of pick-up is essentially a double eccentric column. It has an advantage over a single eccentric column in that it is not sensitive to end moments. In an eccentric column, the direct stresses are superimposed upon the bending stresses, increasing those in the inside gages and reducing those in the outside gages. Elmer Ward, president of the Task Corporation, developed an ingenious means by which the problem of not getting equal and opposite stresses can be overcome. The section is modified, with the center portion upon which the gages are mounted displaced outward. This puts the outside gages further away from the neutral axis to increase stress and the inside gages closer to it to reduce the stress. The reduction and decrease is designed to offset the direct stress effect, so that the load will cause an equal tension and compression in the respective gages. (Use of this idea should be negotiated with the Task Corporation).

Compared to the direct tension-compression method, the disadvantages of the 'race track' or any eccentric column pick-up system are, in general, greater deflection and non-linearity. Non-linearity is, as a rule, not appreciable, except where high unit stresses are employed. An increase in eccentricity will reduce the non-linearity, but it will increase the deflection.

11.2 Hinge Moment Measurement

One of the earliest applications of the electric strain gage in wind tunnel model work was for measurement of control surface hinge moment. The usual method for this employed by North American Aviation is as follows: The control surface is mounted on ball-bearing hinges. Extending forward from the surface, and within the airfoil contour, there is a cantilever beam on which are mounted the strain gages for moment pick-up. The beam is mounted to the control surface on the angle setting index shaft or, if room for this is not available, angle brackets are used. Load is transmitted from the cantilever beam to the airfoil by means of a ball-bearing roller mounted at the forward end of the beam. The roller bears on hardened parallel plates mounted in the airfoil. The beam should be as close as possible to one of the hinges. Otherwise, bending in the surface will cause a deviation in angle position. (See Figures 17 and 18.) Also, for a single-piece surface, only two hinge bearings should be used. Otherwise, deflection, either in the airfoil or surface, will cause binding and deviations in the hinge moment reading. If the surface is too long to be supported by two hinges, it should be made in two pieces, each with independent support. The two pieces may then be connected together by some type of flexible coupling.

Another method sometimes suitable for hinge moment measurement is the use of the torque tube, the pick-up principle of which has been described previously. Suitable flexures are used at each end to ensure transmission of torque only.

In certain cases where measurement of hinge moment or torque is required, the 'cruciform' type of pick-up is the most suitable. It is particularly useful where the torque to be measured is relatively low, and where it is necessary to also transmit bending moment. In such a case, if a torque tube were to be used, a wall thickness sufficient for the bending might be so great that sensitivity for torque would be too low.

The 'cruciform' consists of integral vertical and horizontal beams crossing at their centers to form an 'X' or 'cruciform' section. This section is milled into a bar for some given length. The beams take the bending. Torsion subjects the ends of these beams to bending toward the outer face, with compression on one side and tension on the other. Strain gages then are mounted on these areas for sensing the torsion.

11.3 Airfoil Force Measurement

Measurement of root bending moment and torsion is one of the most common forms of airfoil force measurement. The gages are mounted near the wing root to pick up the bending moment in that region. Gages are also mounted in the area, and on or near the neutral axis, to pick up the torsion. The gages can be mounted on recessed areas in the surface of the airfoil, but it appears to be preferable to mount them on a male tongue extending into the fuselage, which is recessed around the tongue in this area to provide clearance. The tongue, then, is supported inboard of the gages.

The instrumentation described results in a two-component balance for the airfoil, giving bending moment and torsion. When the gages are mounted on a tongue, the use of two sets of bending moment gages, spaced a reasonable distance apart spanwise, will result in a three-component balance. The three-component balance will give torsion and two bending moments, from which it is possible to calculate normal force and its center of pressure position, both spanwise and chordwise.

To obtain enough unsupported length, the tongue is usually extended outboard the required distance into the airfoil. In cases where the tongue is integral with the airfoil, the extension is made by the use of two spanwise slots extending from the base or root. The tongue part may then be made rectangular in section and recessed below the airfoil surface to provide clearance for it and for the gages mounted on it. Plates mounted to the airfoil are then used to cover the tongue and to form the airfoil contour over it. (See Figure 19).

11.4 Internal Balances

Supersonic testing has brought about the use of the sting-supported model with a six-component internal balance. The balance, 2 or 3 in. in diameter by about 1 ft in length, is required to do the job formerly done by the massive external balance. With the high loads now in use, design of such a balance within the space limitations presents quite a problem.

There are various types of internal balances in use, some with ball bearings and rollers, some purely elastic. Of the elastic type, there are various kinds, the majority of them using the electric strain-gage principle.

For its larger models, North American Aviation has developed and uses a cylindrical type of balance. The principle is very simple and very direct. The balance consists of an inner cylinder enclosed within an outer cylinder. The inner cylinder is supported by the sting and forms an extension of it. The outer cylinder supports the model. Force measurement is obtained through the connections, by means of which the inner cylinder supports the outer cylinder.

For all except rolling moment, simple force-measuring links are used. There are two links for normal force, one at the forward end of the balance, and one at the aft end. There are two side force links, front and aft. One link on the cylindrical axis is used for chord force. A torque tube torsion element is used for rolling moment. (This rolling moment feature is a North American Aviation contribution to the design of this type of balance).

The original balance, designed and built by North American Aviation, was 2.125 in. in diameter and had a total normal force capacity of 1078 lb. The simple eccentric-column type of force link was used in this unit. The balance was very successful, and it has been used by many aircraft companies. The Southern California Cooperative Wind Tunnel (CWT), of which North American Aviation is a member, adopted the design. Two additional balances were constructed, and the balance was designated CWT No. 3155. (See Figure 20.) The Northrop Aircraft Company built several copies enlarged to 2.5 in. in diameter, and the Lockheed Aircraft Company built some modified versions.

The second balance was designed by North American Aviation for CWT. It was 2.5 in. in diameter and had a total normal force capacity of 2000 lb. An early type of tension-compression unit was used for the force links. The balance was designated CWT No. 3161. Three such balances were constructed, two for CWT and one for Convair. This balance was also very successful. Several other balances following the same general design were constructed by other agencies.

Features of a balance of this design are high accuracy, low interaction, high load capacity, and low deflection. Errors or interactions are usually well below one per cent of the corresponding rated load.

Since failure of a force-measuring unit would, in most cases, not result in the loss of the model, a factor of safety of 2, based on the yield strength of the material, is generally used for their design. For the structure, particularly that of the inner cylinder, where failure might be catastrophic, a relatively high factor of safety, perhaps as high as 5, may be used.

The load capacity for a balance of this type, and in general for any type of balance, is the function of the square of the dimension. The moment capacity is a function of the cube of the dimension. A balance 2.5 in. in diameter by a little over one foot long might have a total normal force capacity of about 3000 lb, and a rolling moment capacity of about 3000 in. lbs. These are representative, not limiting values. A special design has already been developed with much greater rolling moment capacity.

One major difficulty has been experienced with this type of balance. This difficulty is an error in chord-force reading due to temperature differential within the balance structure. The temperature difference between outer and inner cylinders causes a change in dimensional relationships which, due to the stiffness of the flexures (particularly those of the rolling moment element), results in a shift in the chord-force reading. The error is determined by the temperature differential, the geometrical arrangement of the balance, and the stiffness of the flexures. Other things being equal, a balance with twice the capacity would have flexures twice as thick, or eight times as stiff, and the error would be eight times as large. This explains why the error is more pronounced in a compact high-load balance. It should be made clear that the error under discussion is one in chord force, resulting from differential thermal expansion of the balance as a whole. The error does not result from temperature changes in the individual gages.

Five thermocouples are mounted on the balance, one at each end of each cylinder, and one on the chord-force link. The purpose of these thermocouples is to determine whether or not the temperature differential is sufficient to cause a significant error and to enable estimation of a correction, if required.

For many tests, this error due to temperature differential has not been significant. However, the problem becomes more apparent with the very compact high-load balance now required. Also, in some tunnels with relatively high temperature operation, and with duct inlet models which at high speeds have relatively high temperature differences and which need especially accurate chord-force measurement, the error may be of sufficient magnitude to rule out use of this balance.

Confronted with the problem of providing an elastic balance suitable for testing a duct inlet model in a wind tunnel of relatively high temperature operation, North American Aviation developed a temperature-compensated balance configuration. The balance was made symmetrical about a fore-and-aft center point. Fore-and-aft normal-force links were identical, and side-force links were identical. Two chord-force links and two rolling-moment units were used, one of each forward and one of each aft. With this arrangement, there can be a large temperature difference between the outer and inner cylinders with no error in chord-force reading, since effects from the forward part and cancelled out by effects from the aft part. To permit the use of high unit strain, the 'race track' type of force pick-up was specified for the balance. (See Figure 21).

The actual design and construction of the balance was assigned to the Task Corporation, which specializes in this field. They requested and received from North American Aviation permission to use the temperature-compensation feature in other balances of their manufacture. In return, North American Aviation was given the right to use ideas developed by the Task Corporation in the design of the balance, which included, in particular, the modified 'race track' force link.

The performance of the balance exceeded expectations. Even with substantial temperature differential, errors in chord force have been below 0.25%. The Task Corporation has built or is building a number of balances incorporating the temperature-compensation feature. These balances are being built as small as 0.75 in. in diameter, and as large as 8.0 in. in diameter. (Of these balances, two are for North American Aviation, several are for CWT, one is for Convair, two are for the McDonald Aircraft Company, and others are for various government laboratories throughout the United States).

In some cases it is not feasible to use an internal balance as a unit. Either the space it would occupy is not available, or the load requirement is beyond its capacity. In such cases, a built-in balance is used.

The built-in balance employs the same general principle as does the cylindrical balance. However, the fuselage itself, instead of the cylinder, constitutes the outer structure. This permits, in essence, a larger balance; hence, load capacity is greater. In this case, however, the fuselage must be of Armco Steel construction, the same as the rest of the balance structure, to avoid problems from differential thermal expansion. The inner structure may be a cylinder, or it may be of some other suitable shape. Five force links and a rolling-moment torque unit may be used, as in a cylindrical balance. If the space arrangement is not suitable for this, six or more force links may be used. (See Figure 22).

If adequate space were available, an interesting arrangement might be the use of three force links (one for normal force, one for side force, and one for chord force) with three torque units (one for pitching moment, one for yawing moment, and one for rolling moment). Data would then be given in the desired direct form.

Discussion of calibration rigs for internal balances, or treatment of external balances is beyond the scope of this paper. Two sources for this and other wind tunnel equipment are the Task Corporation, 253 North Fairoaks Avenue, and the Sandberg and Serrell Corporation, 1276 East Colorado Street, both of Pasadena, California, U.S.A.

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Fig.1 B-45 Model

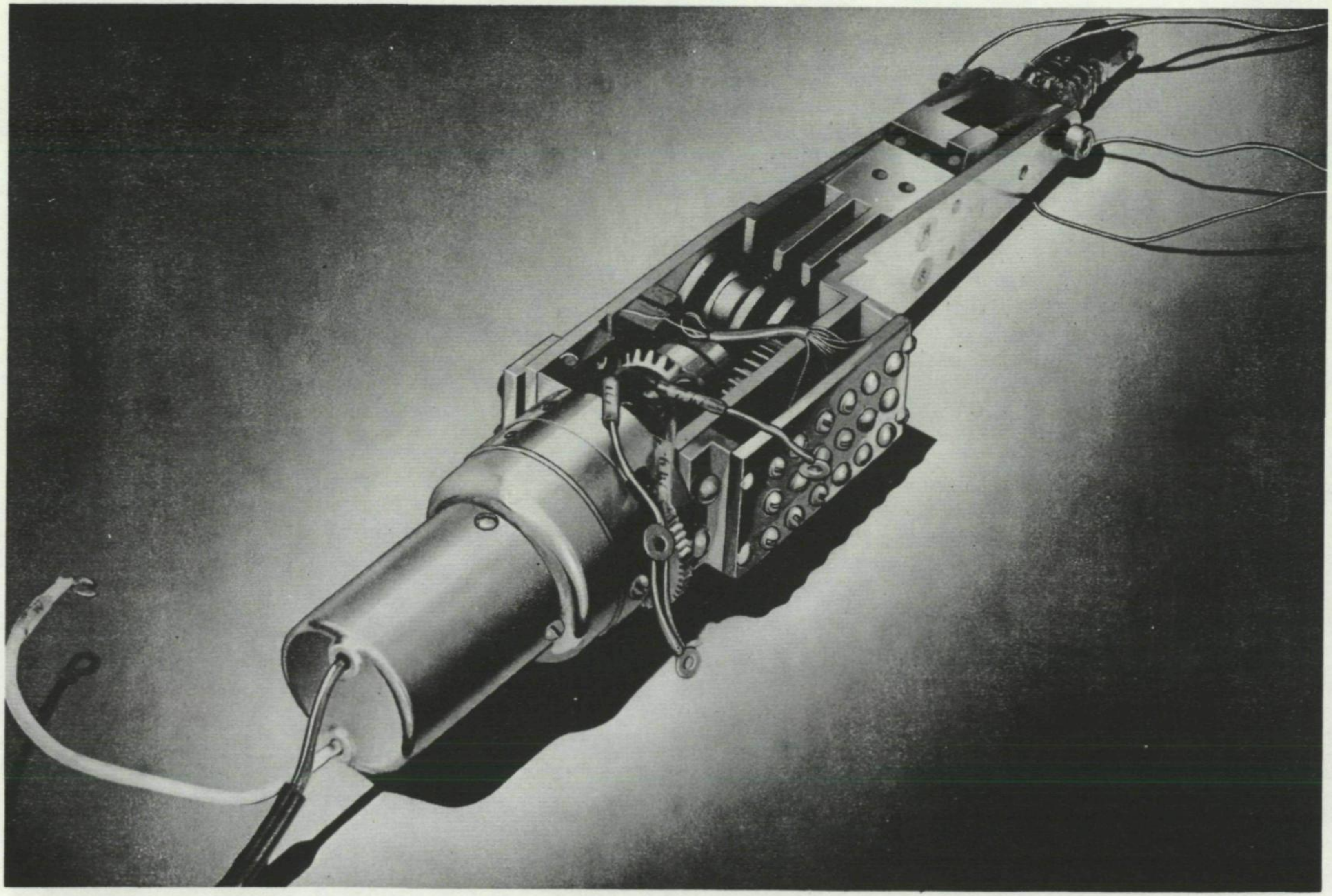

Fig.2 F-100 Spin Model

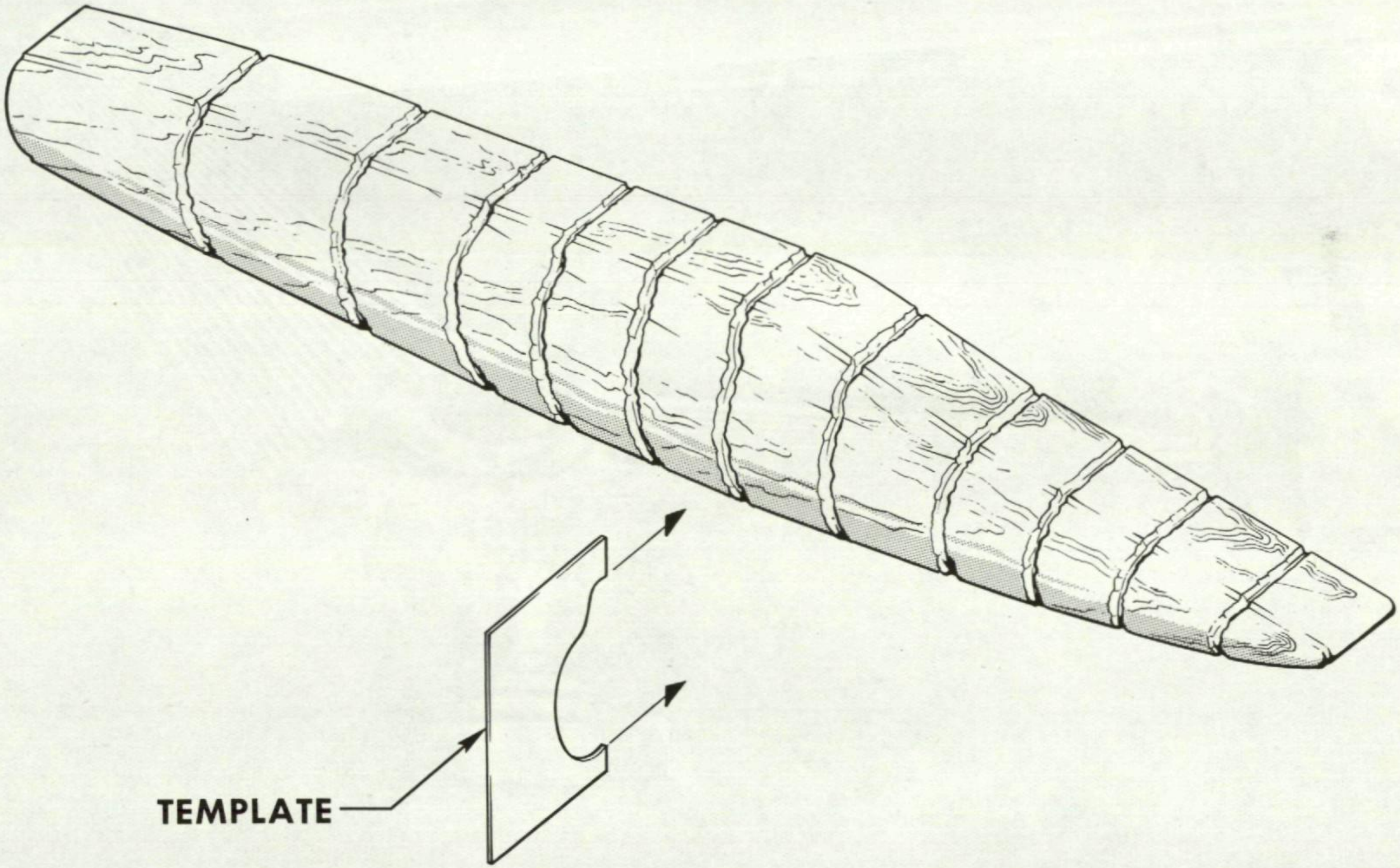

Fig.3 Fuselage Under Construction

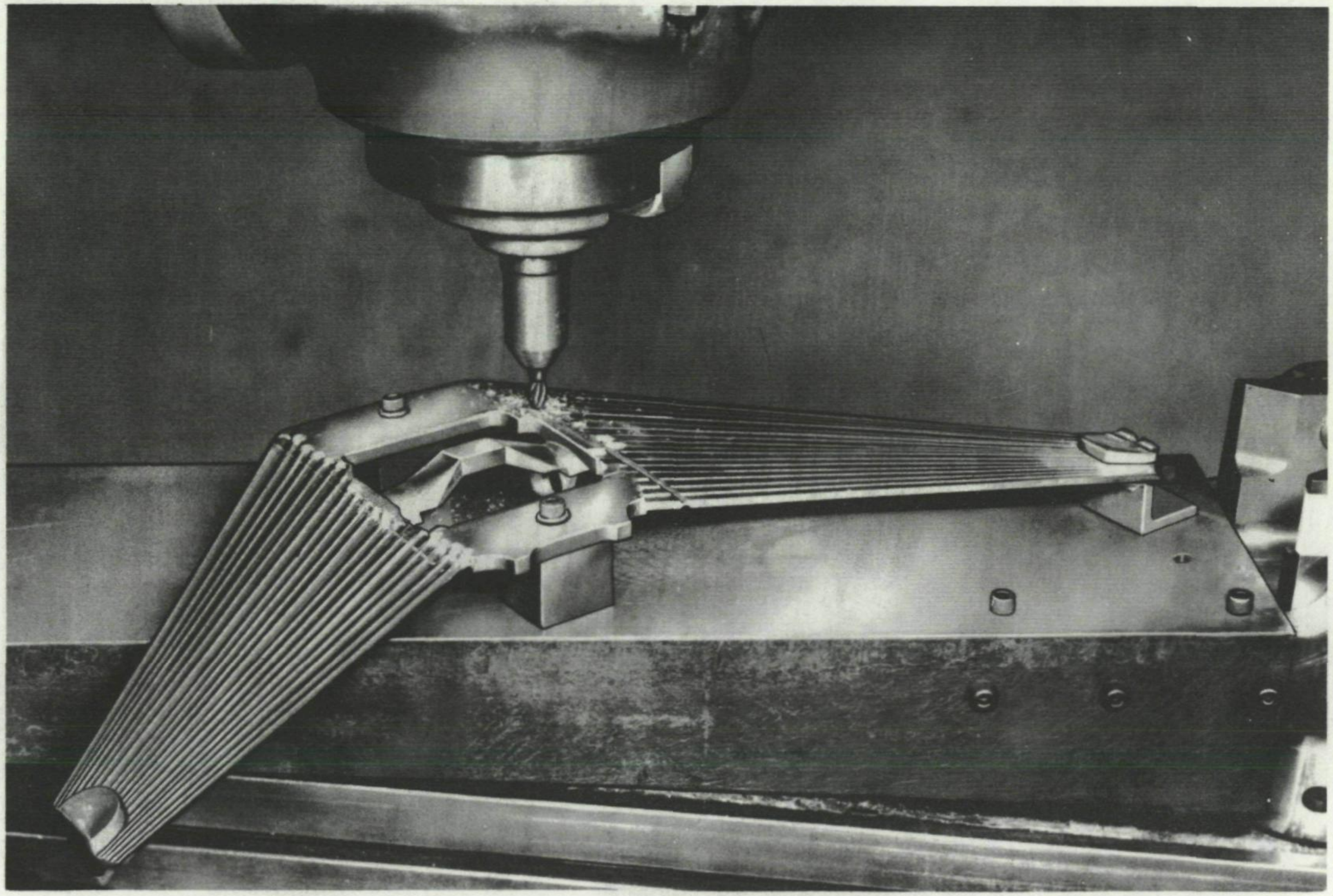

Fig.4 Airfoil in Milling Machine

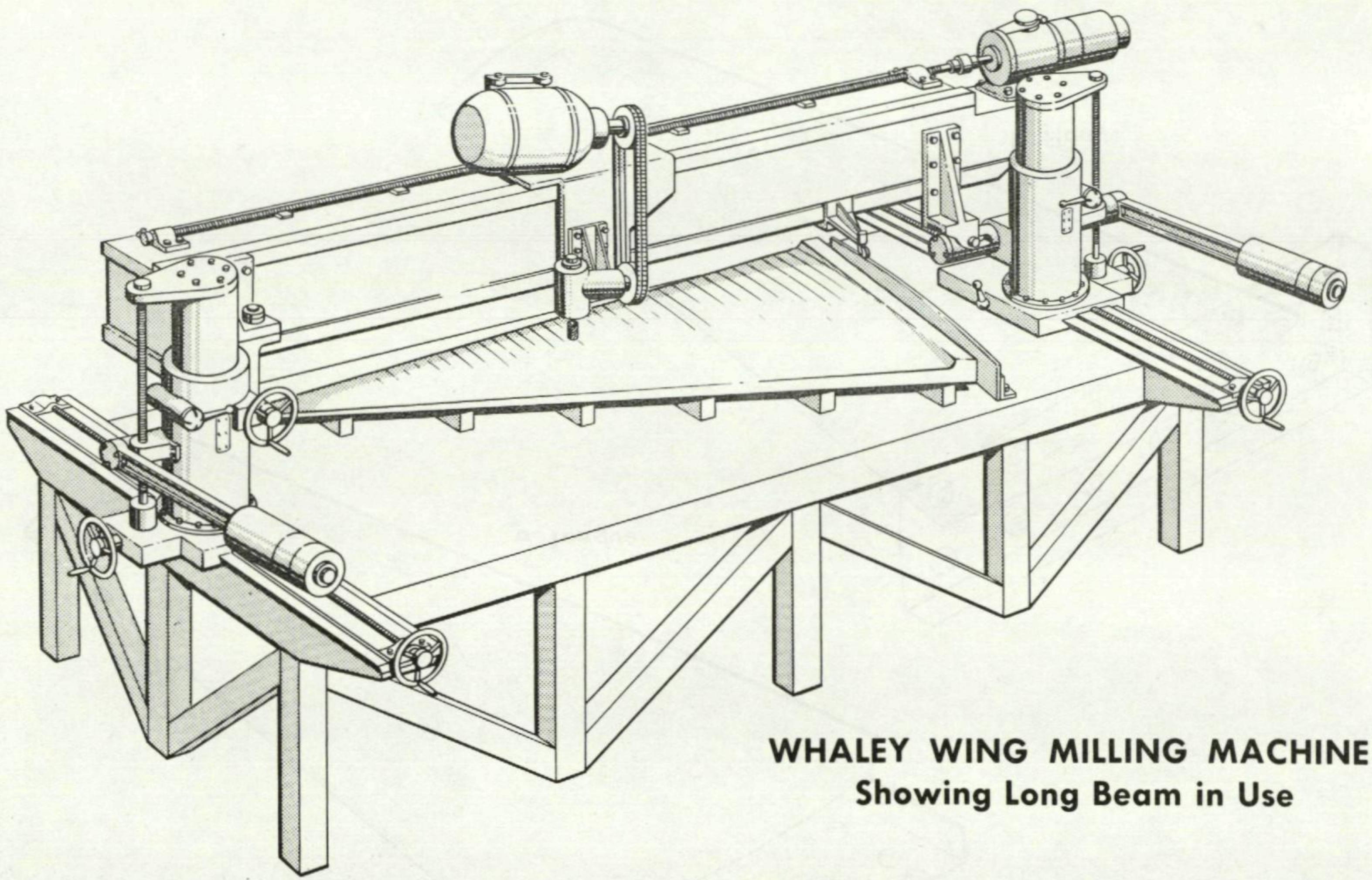

Fig.5 Airfoil in Contouring Machine

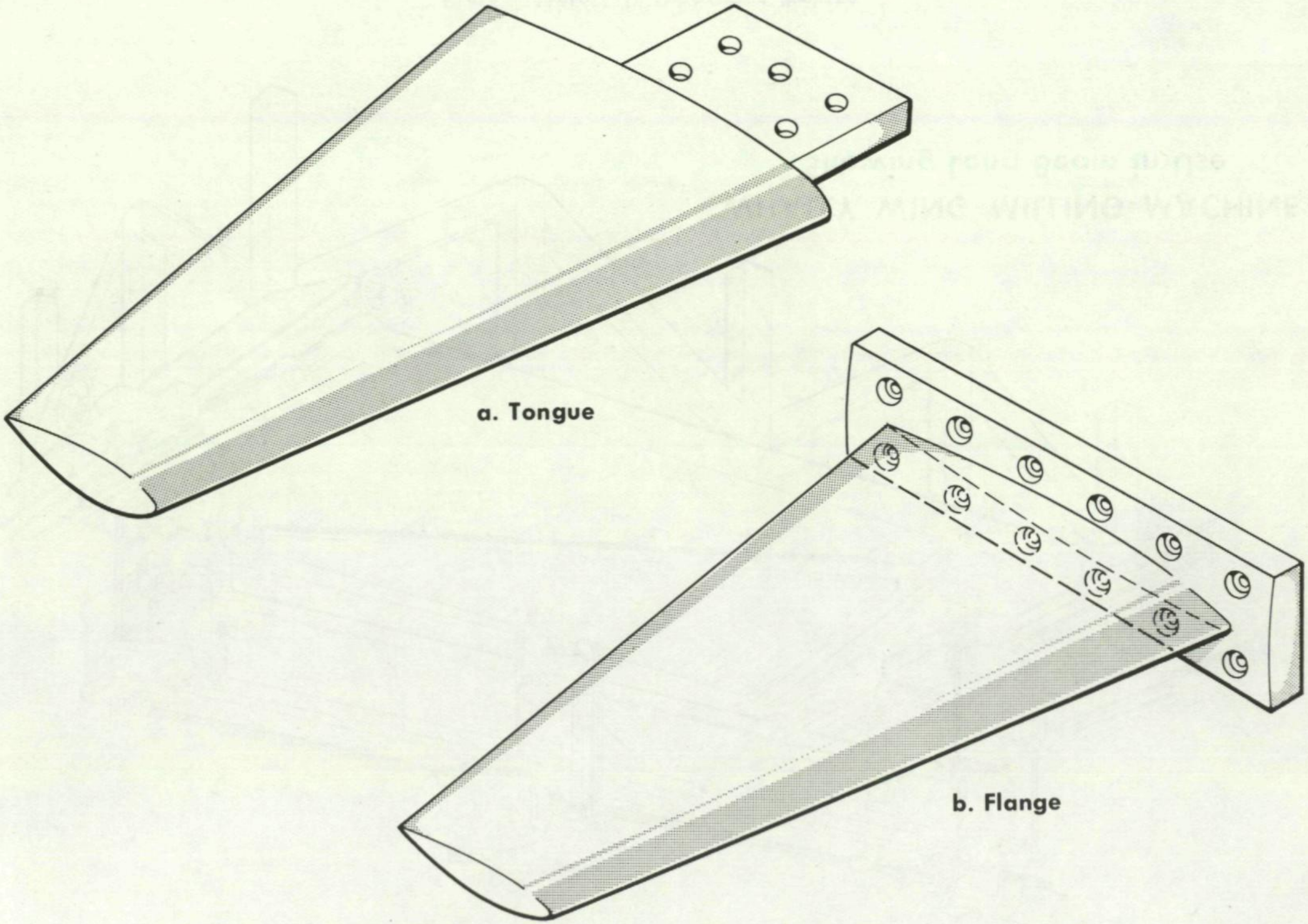

Fig.6 Airfoil Joints

Fig.7 Control Surface Remote Indexing Device

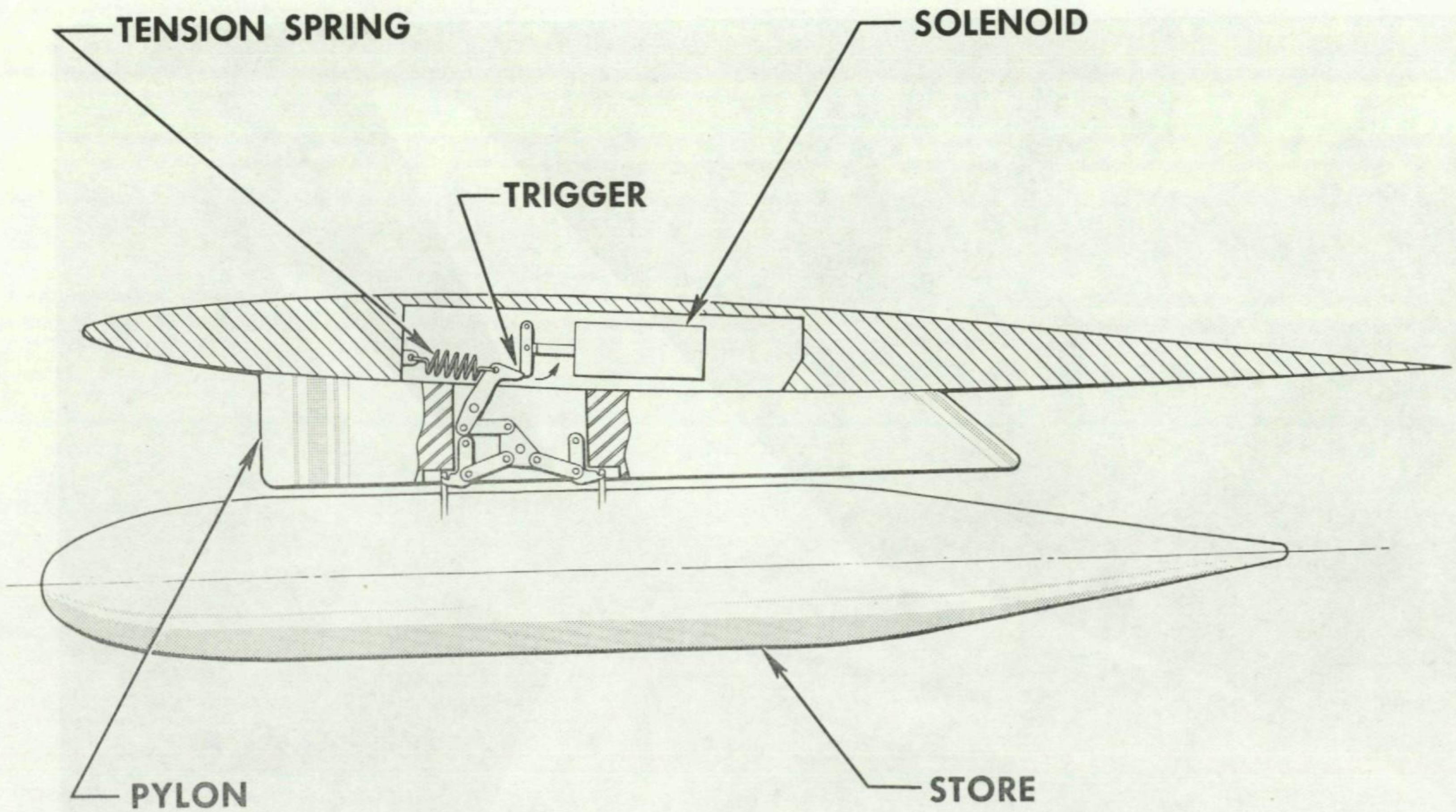

Fig. 8 Fuel Tank Release Mechanism

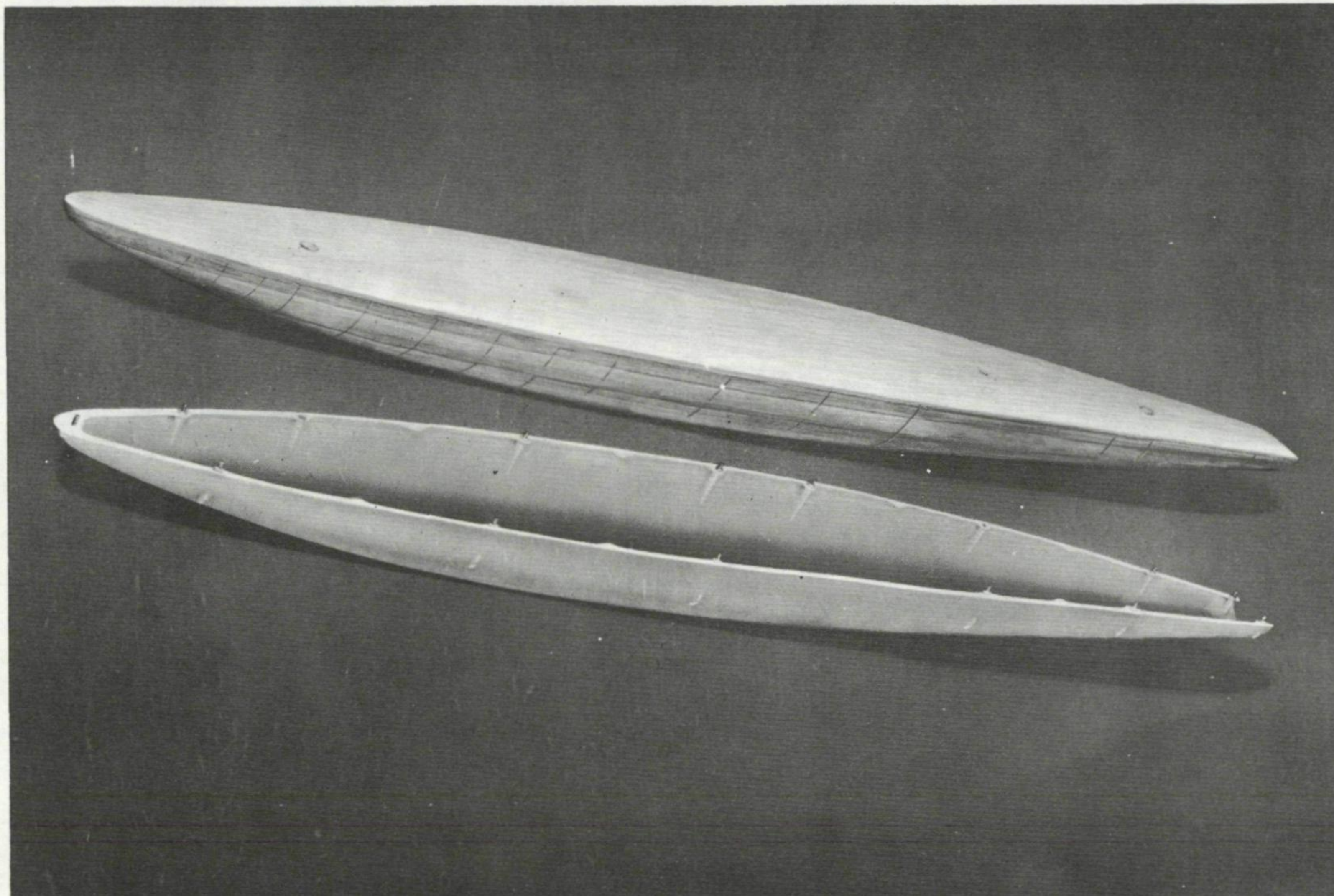

Fig. 9 Jettisonable Fuel Tank Under Construction

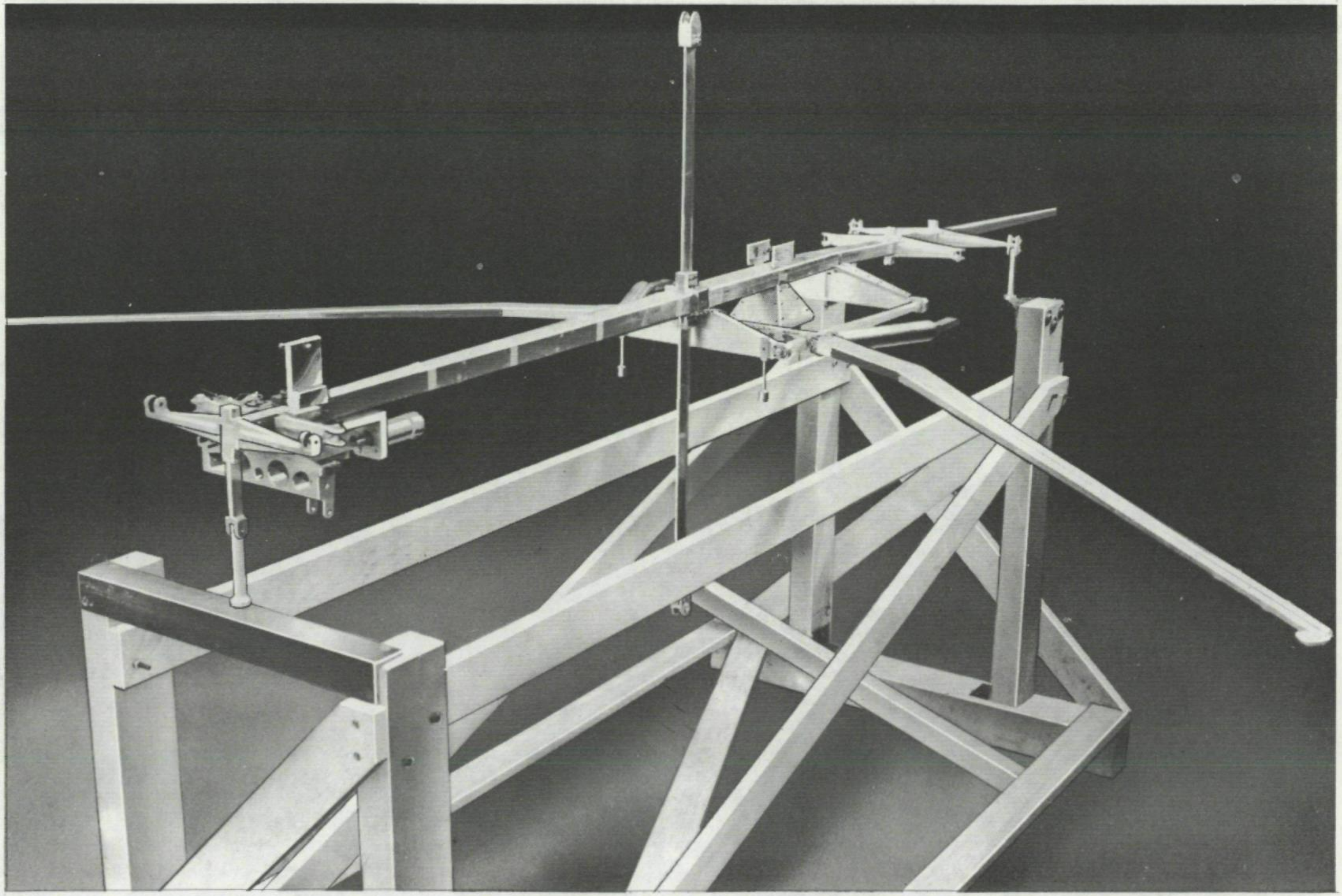

Fig.10 F-100 Flutter Model Skeleton

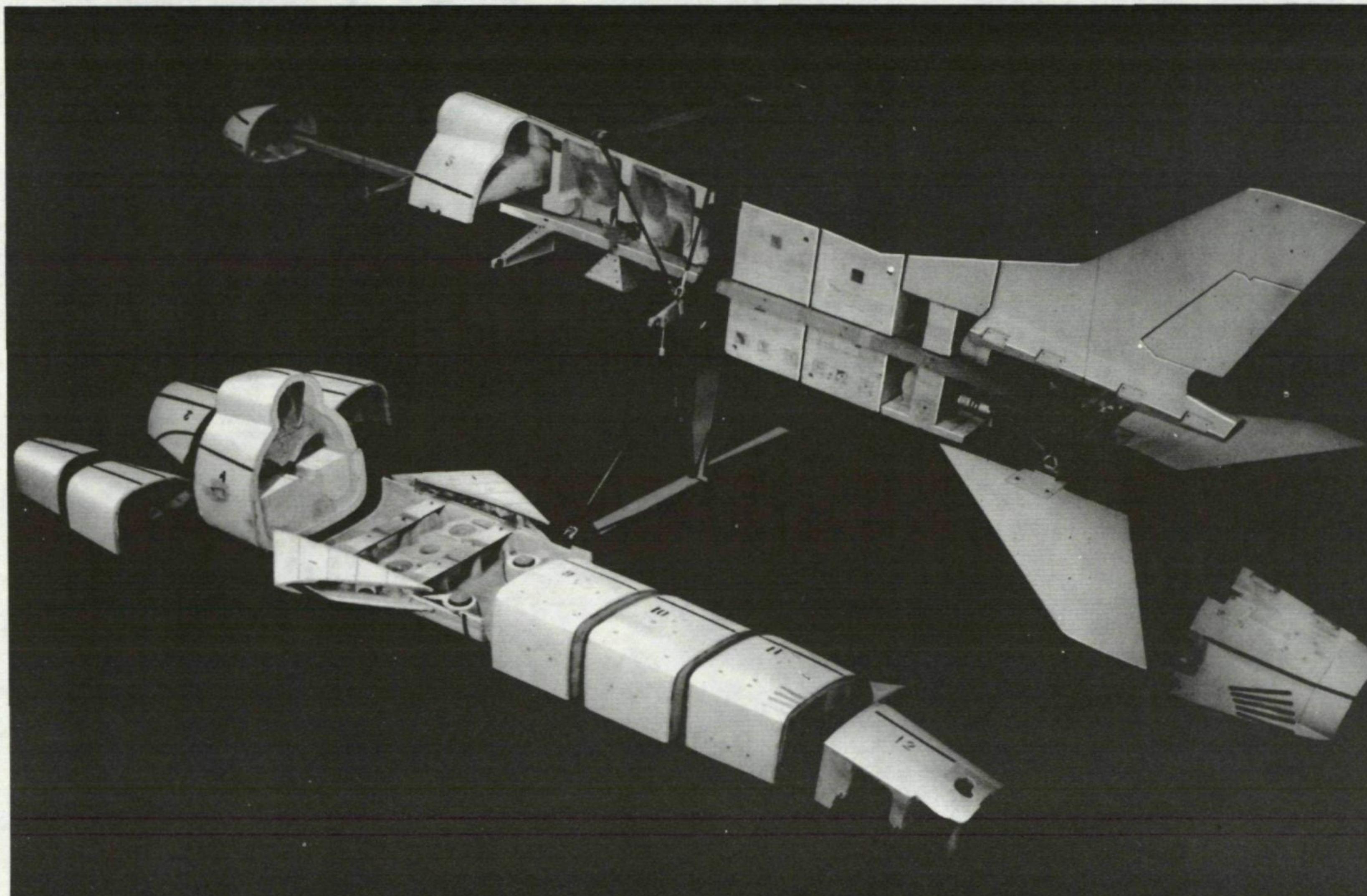

Fig.11 F-100 Flutter Model - Fuselage Being Assembled

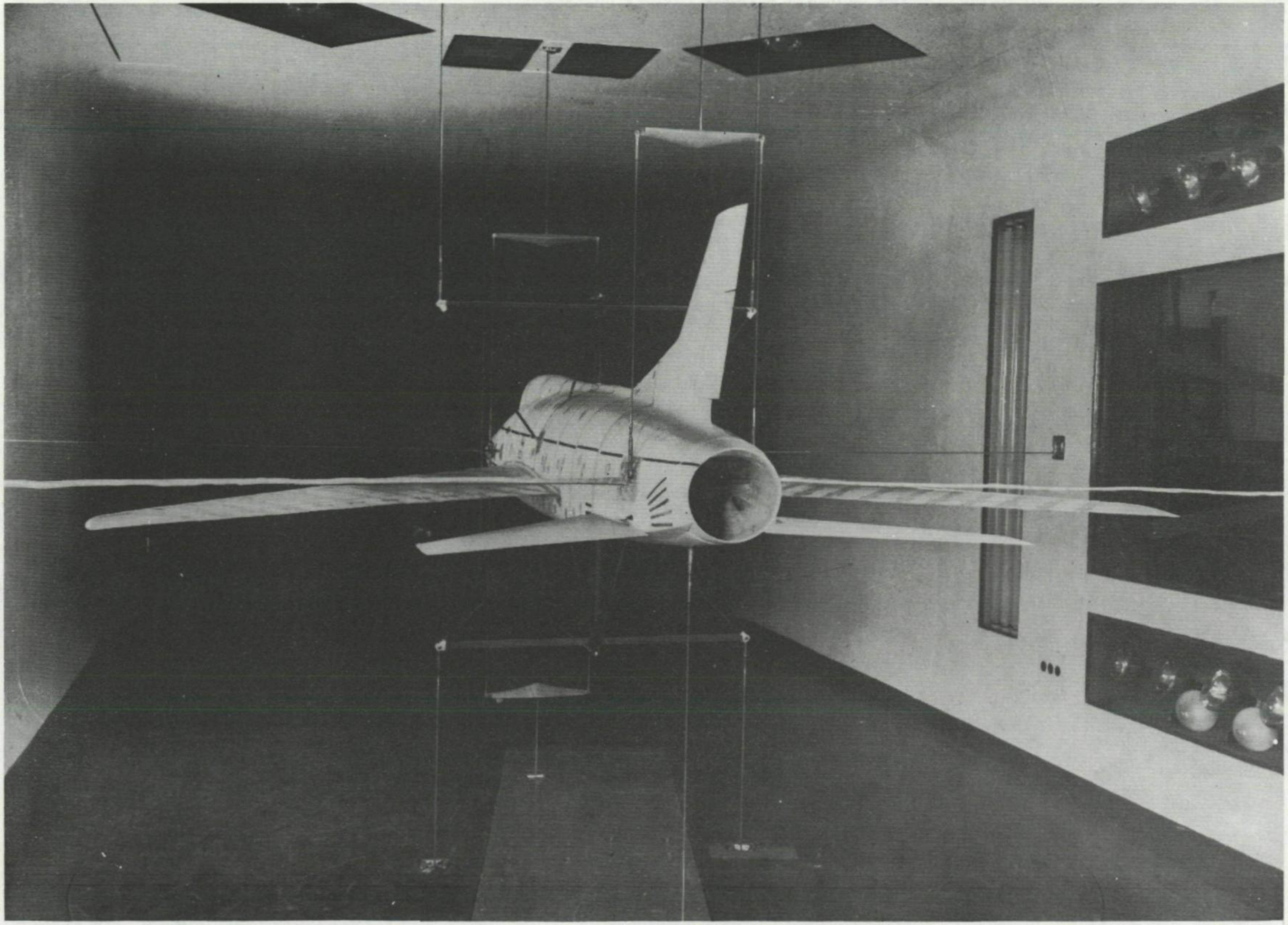

Fig.12 F-100 Flutter Model in Tunnel

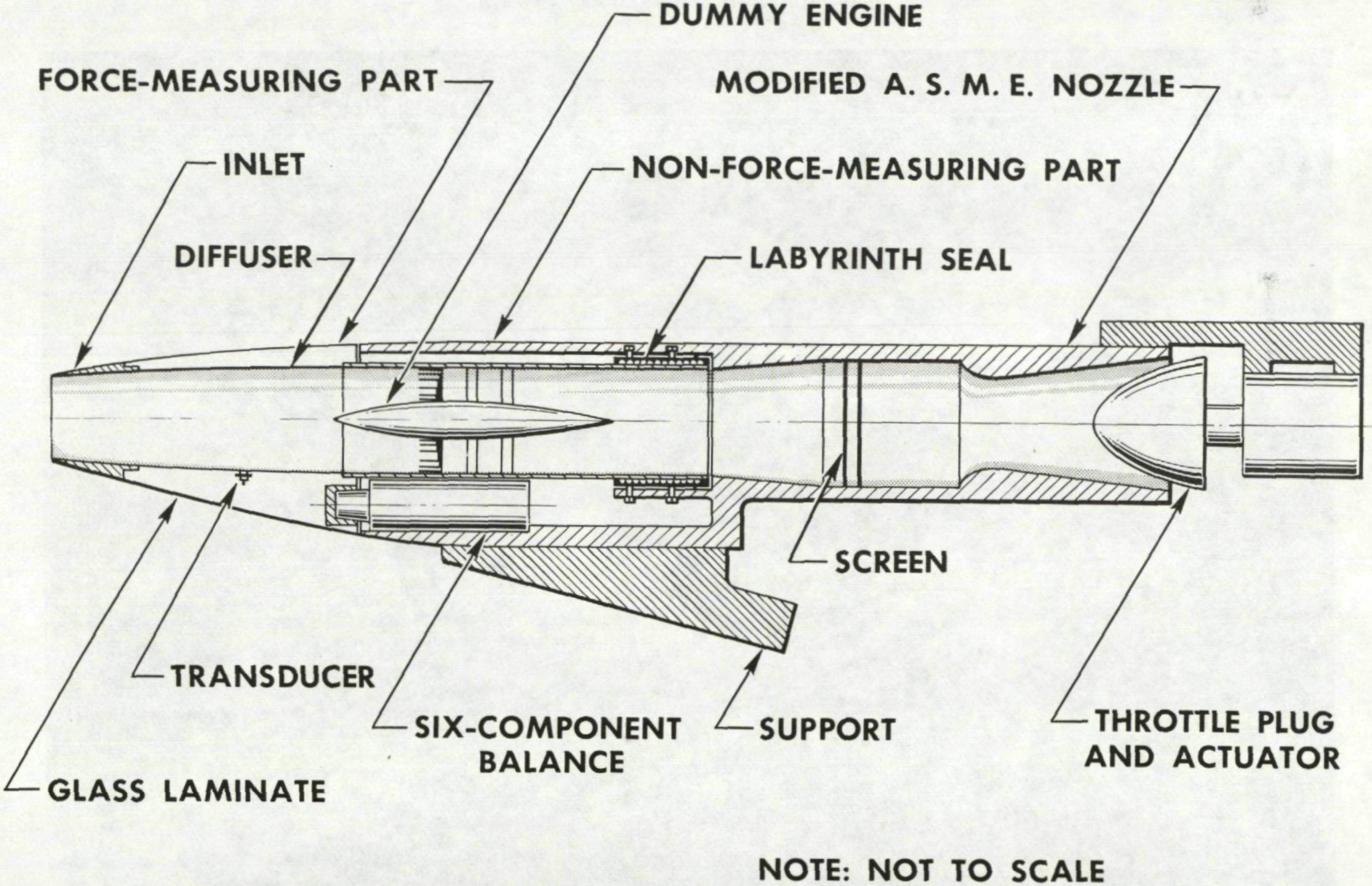

Fig.13 Duct Inlet Model

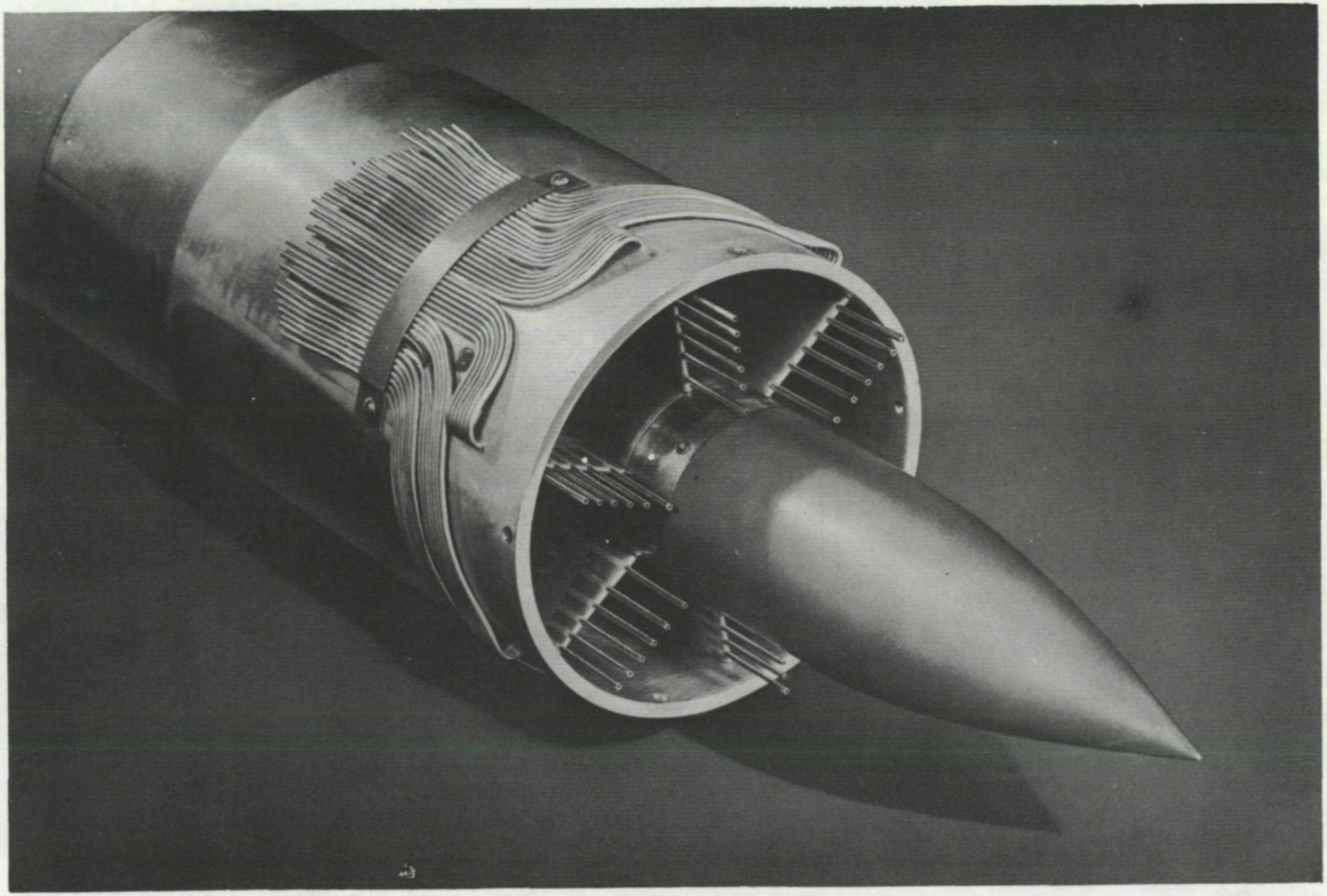

Fig.14 Dummy Engine, Duct Inlet Model

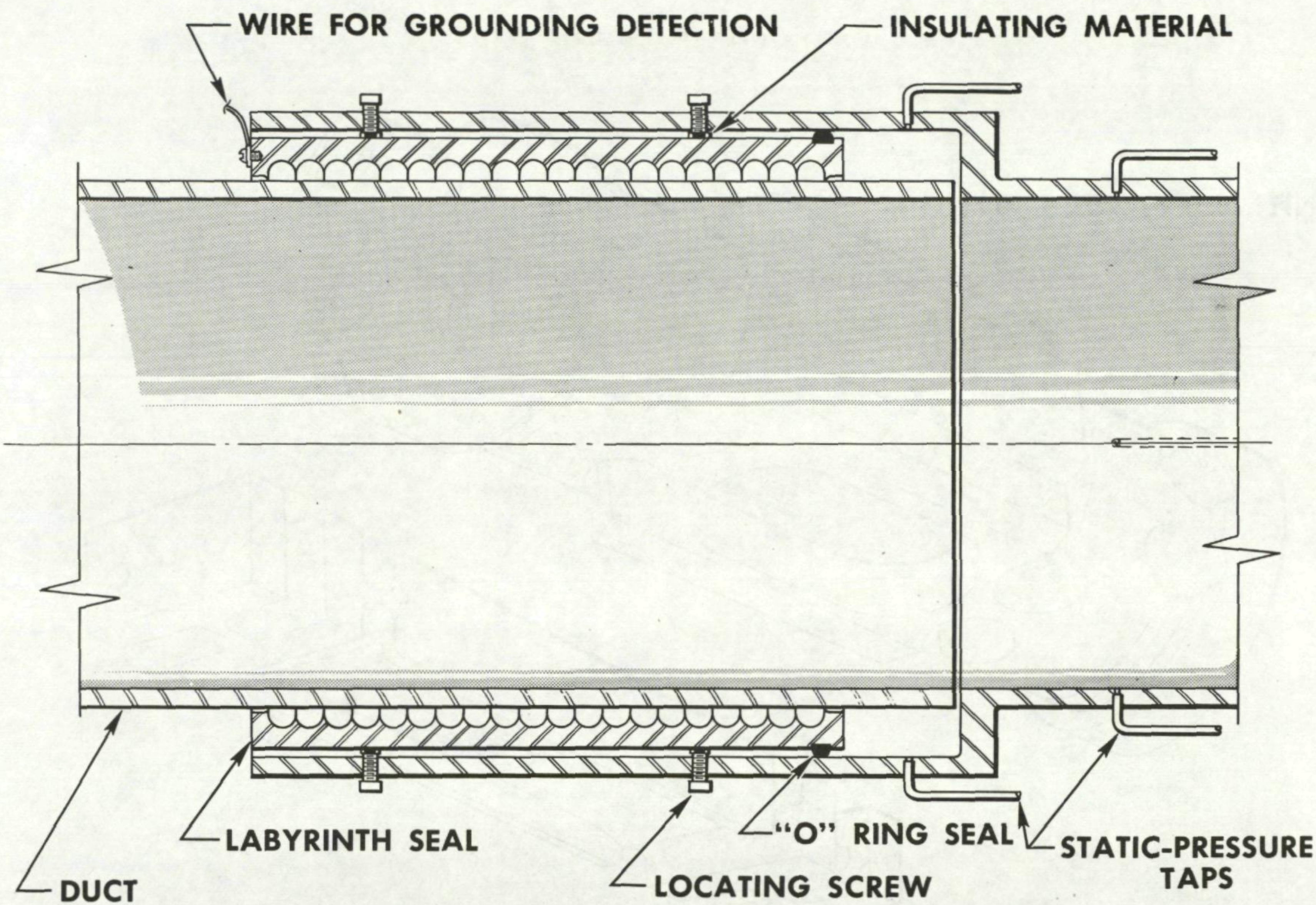

Fig.15 Labyrinth Seal, Duct Inlet Model

FIG. 16A-TENSION-COMPRESSION LINK

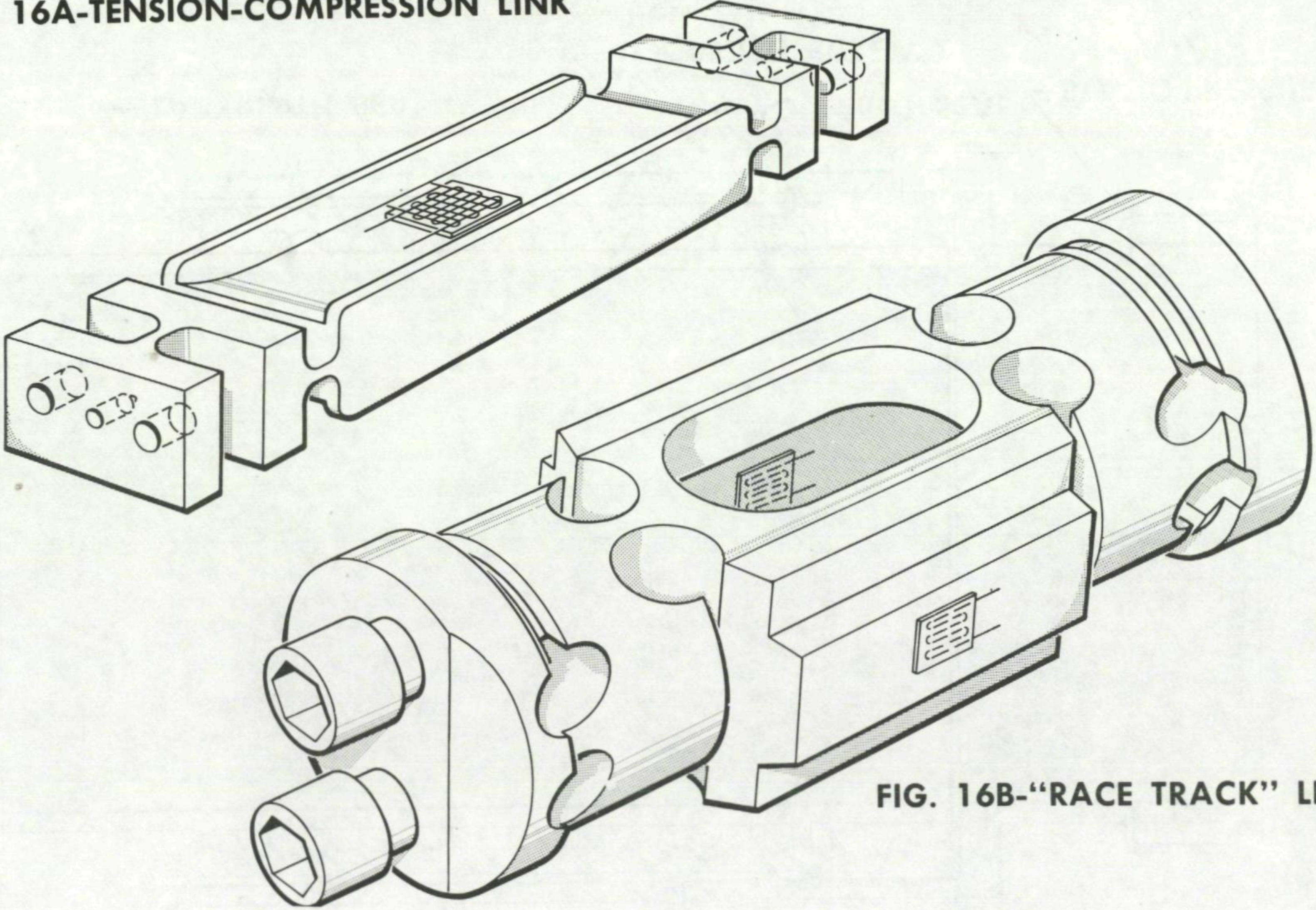

FIG. 16B-"RACE TRACK" LINK

Fig.16 Force Links

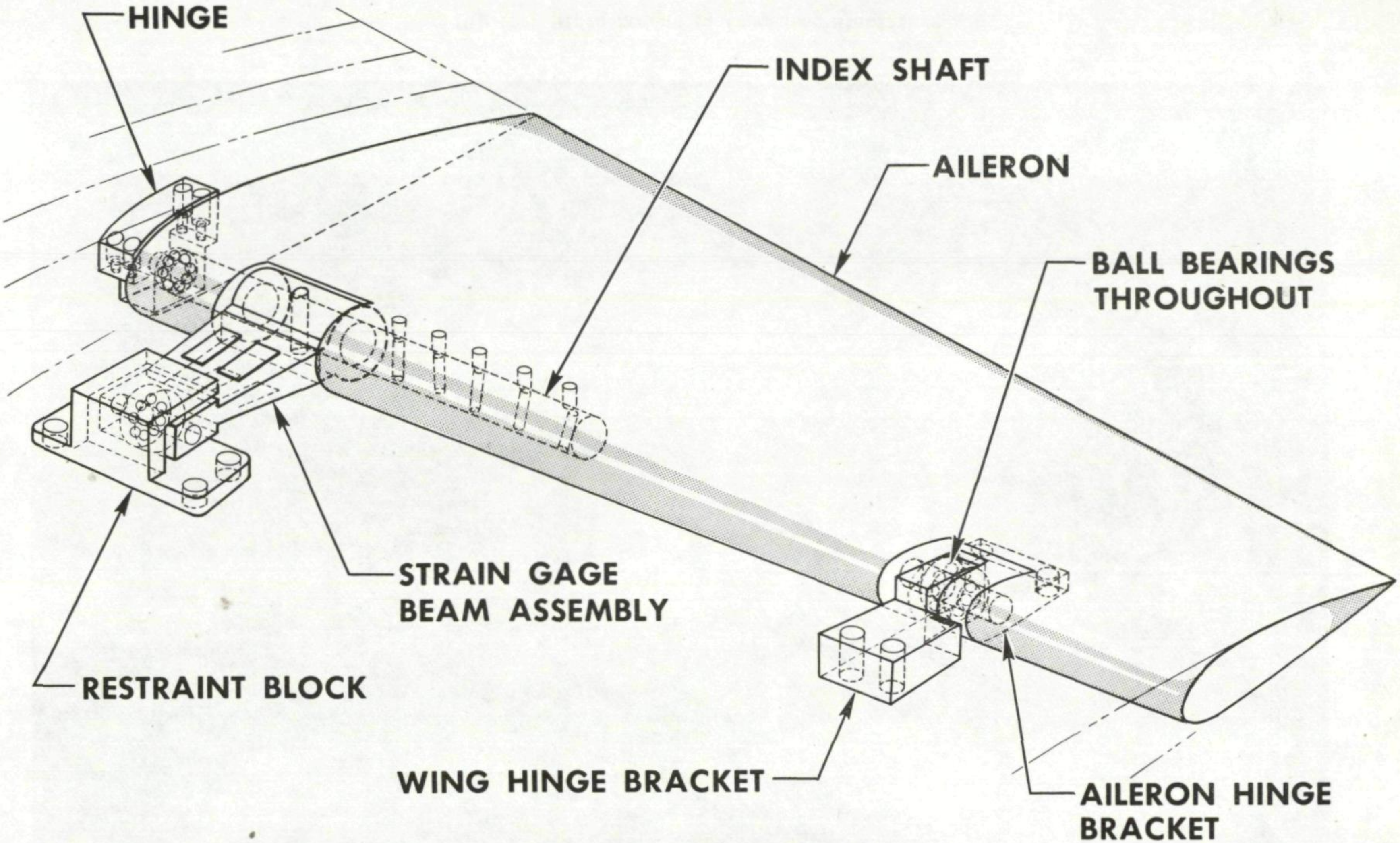

Fig.17 Hinge Moment Instrumented Aileron

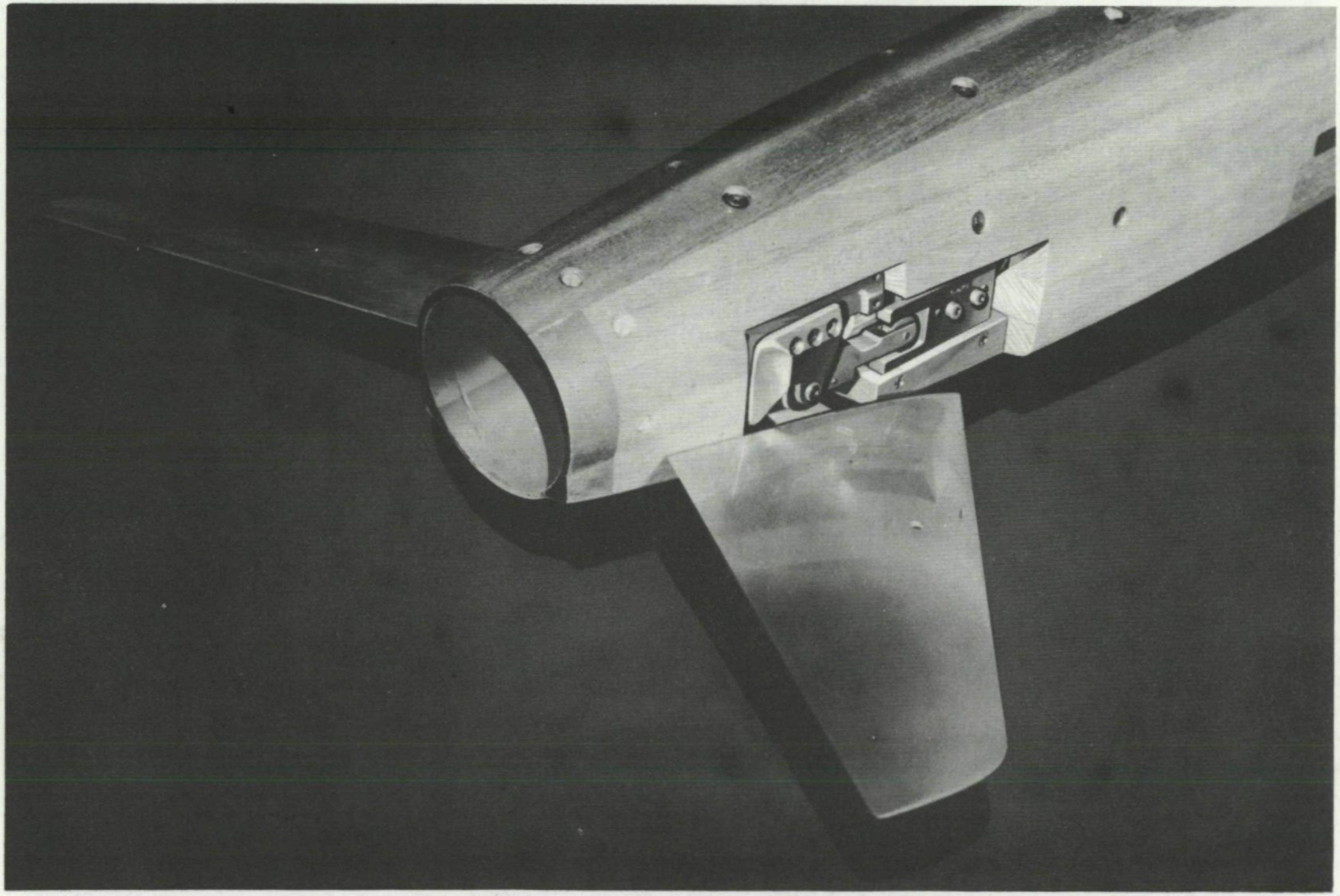

Fig.18 Hinge Moment Instrumented Stabilizer

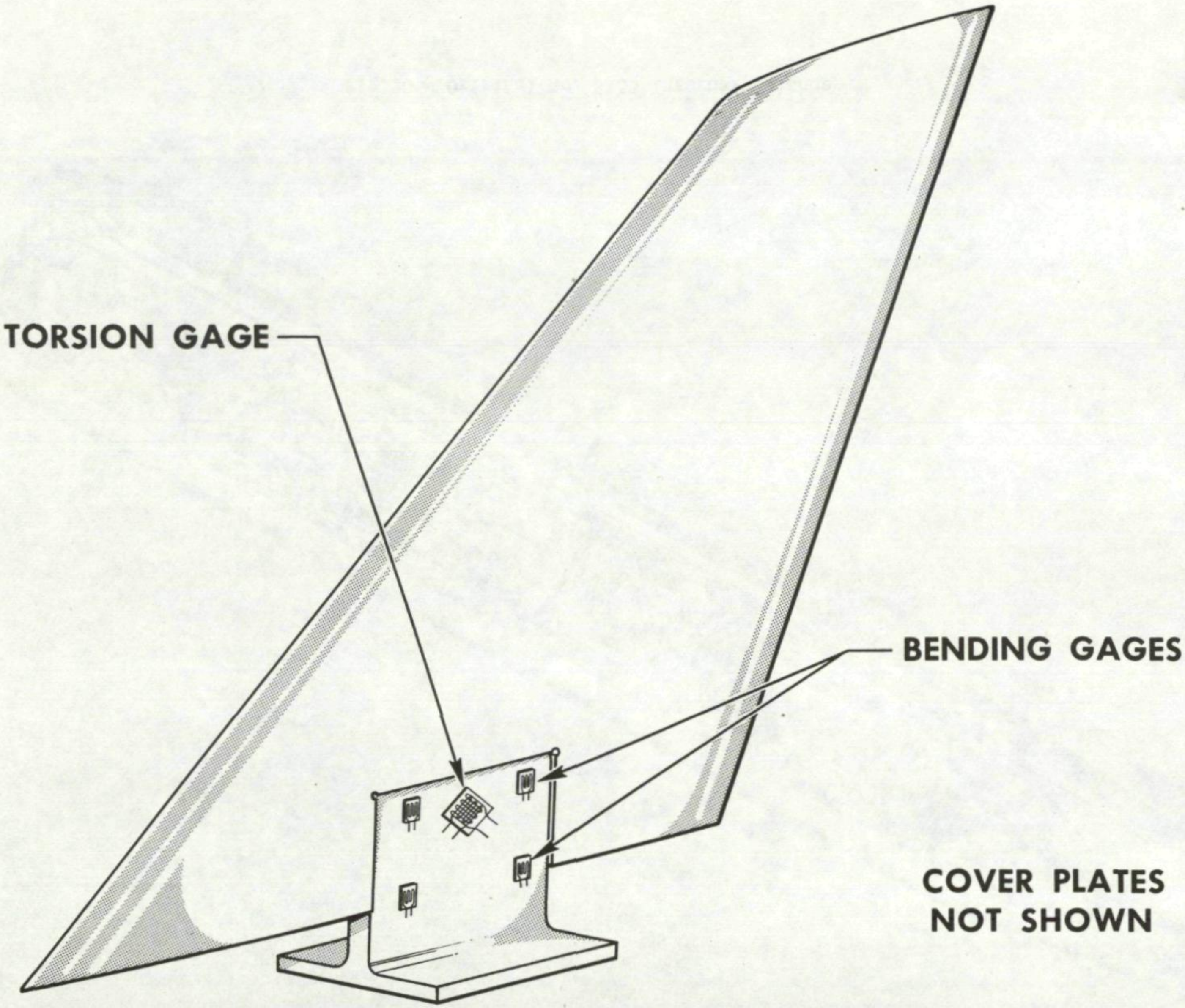

Fig.19 Three-component Airfoil Balance

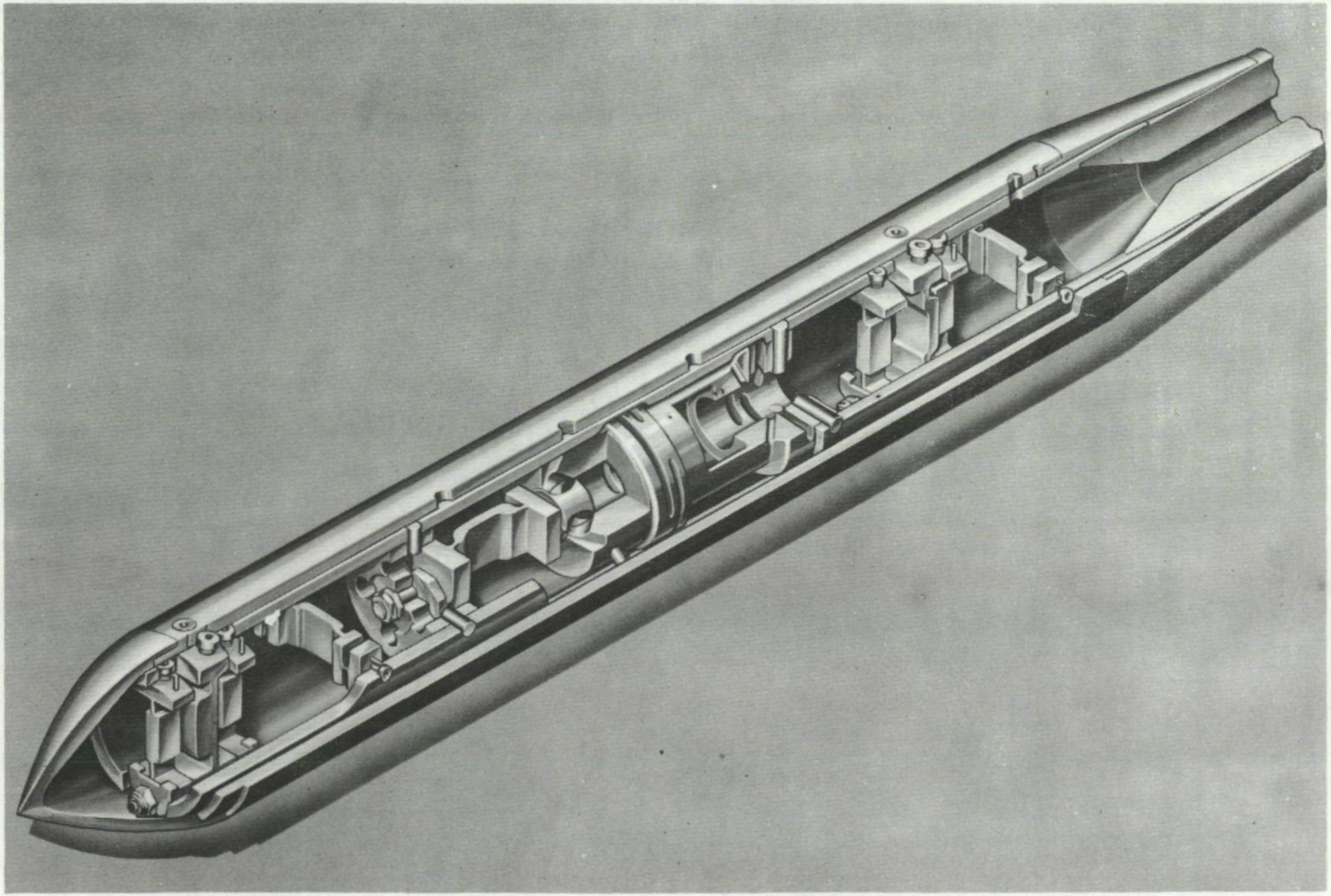

Fig. 20 Original No. 3155 Internal Balance

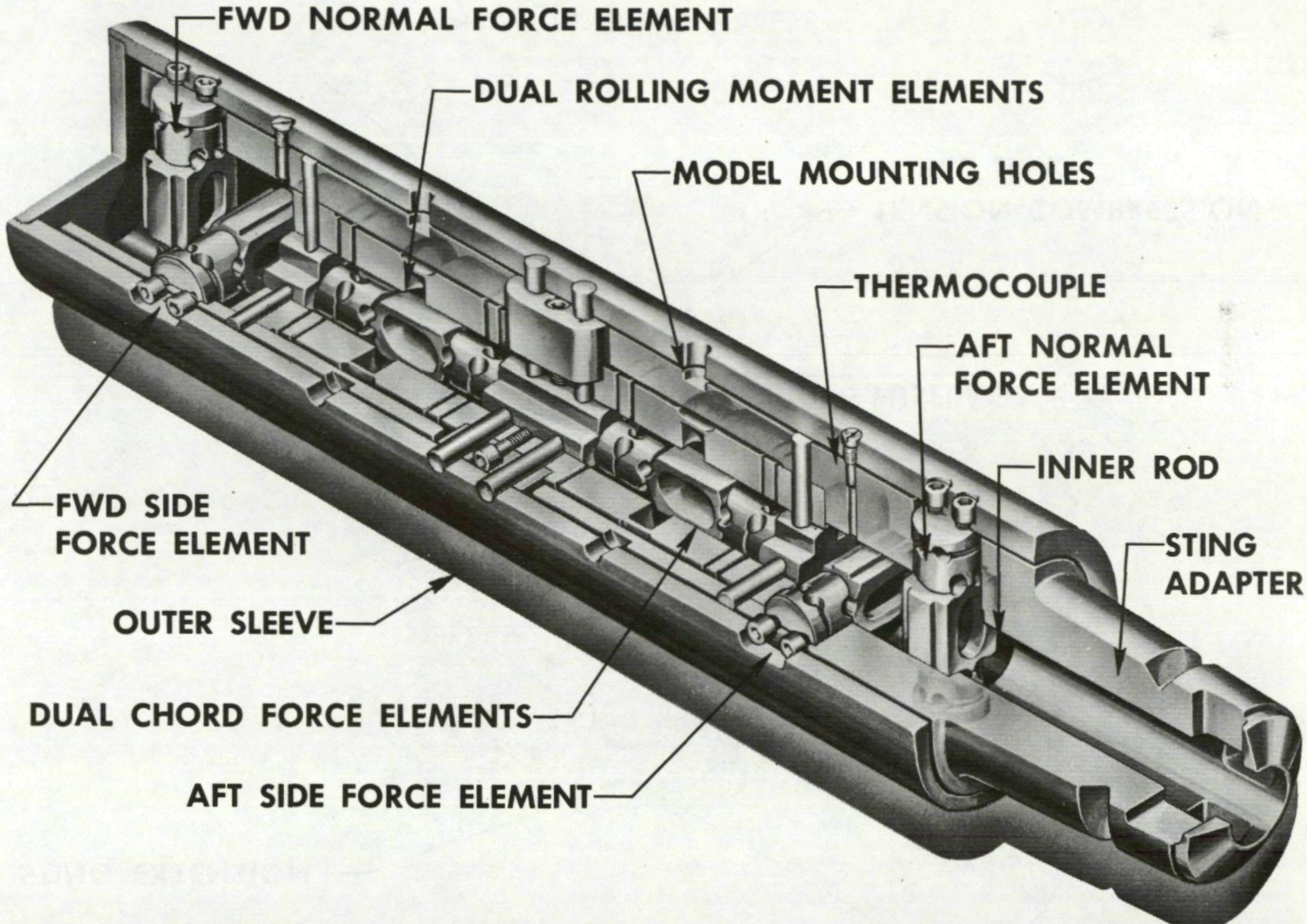

Fig.21 Temperature-compensated Internal Balance

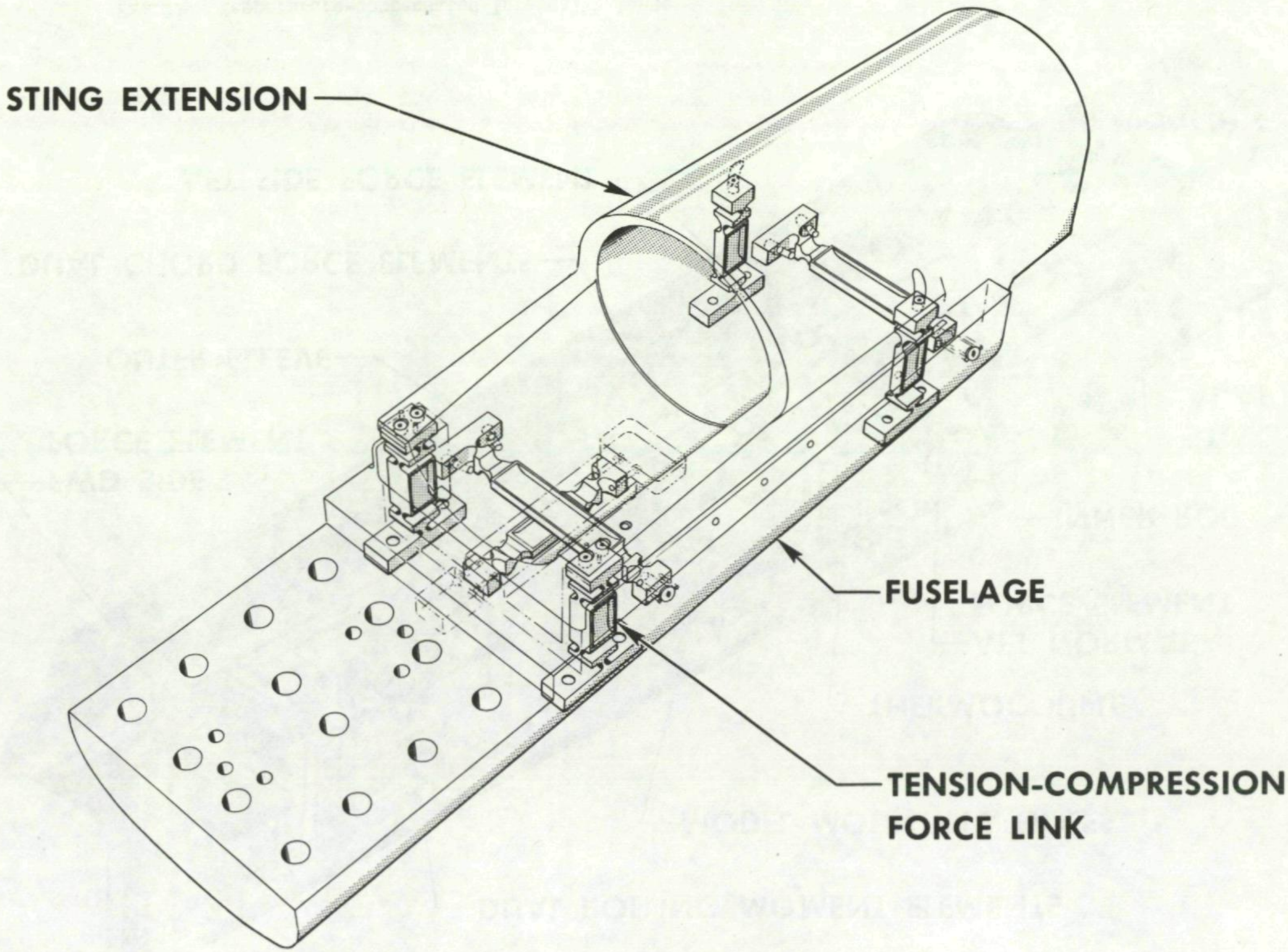

Fig. 22 Typical Built-in Balance

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Davie, R.P.
1956
56 pages, incl. 22 figs, 6 refs.

This paper will deal with wind tunnel models, their design, and construction. It is based on experience gained by the Model Design Group of North American Aviation, Inc., Los Angeles Division, as observed by the author and his associates. Only unclassified material is included. An attempt will be made to avoid giving data already published. It is hoped that this paper will be of value to those concerned with wind tunnel models, particularly to those connected with model design and construction.

Presented at the Eighth Meeting of the Wind Tunnel and Model Testing Panel, held from February 20th to 25th, 1956, in Rome, Italy.

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