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STATIC FORCE TESTS OF A SHARP LEADING EDGE DELTA-WING MODEL AT AMBIENT AND CRYOGENIC TEMPERATURES WITH A DESCRIPTION OF THE APPARATUS EMPLOYED

Robert A. Kilgore and Edwin E. Davenport

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16. Abstract

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Robert A. Kilgore and Edwin E. Davenport
Langley Research Center
Hampton, Virginia

SUMMARY

A sharp leading edge delta-wing model has been tested through an angle-of-attack range at Mach numbers of 0.75, 0.80, and 0.85 at both ambient and cryogenic temperatures in the Langley 1/3-meter transonic cryogenic tunnel. Total pressure was varied with total temperature in order to hold test Reynolds number constant at a given Mach number. The test program was designed with the dual purpose of (1) obtaining experience in a cryogenic wind tunnel with an electrically-heated internal strain-gage balance, the accompanying sting-support arc, and an accelerometer used to determine angle of attack; and (2) investigating any possible effects of cryogenic stagnation temperature on the aerodynamic characteristics of a configuration having flow characterized by a separation-induced leading-edge vortex.

Agreement between the aerodynamic data obtained at ambient and cryogenic temperatures indicates that flows with leading-edge vortex effects are duplicated properly at cryogenic temperatures. The test results demonstrate that accurate aerodynamic data can be obtained by using an internal strain-gage balance and conventional force-testing techniques if suitable measures are taken to minimize temperature gradients across

the balance and to keep the balance at ambient (warm) temperatures during cryogenic operation of the tunnel. The various modifications to the electrically-heated balance and the delta-wing model which were required for successful operation are described in an appendix. Based on experience with the balance used for these tests, suggestions are given regarding the design of balances for use in cryogenic wind tunnels.

INTRODUCTION

It is widely recognized, both in the United States and in Europe, that there is an urgent need for wind tunnels capable of testing models at or near full-scale Reynolds number. Operating a tunnel at cryogenic temperatures, as proposed by Smelt in 1945 in reference 1, is an attractive way of increasing Reynolds number while avoiding many of the practical problems associated with testing at high Reynolds numbers in conventional pressure tunnels.

Personnel of the NASA Langley Research Center have been exploring new aspects of the cryogenic concept and developing the technology required for the application to high Reynolds number transonic tunnels since the autumn of 1971. The results of a theoretical study and the results of a low-speed experimental program have been reported in references 2 and 3. In order to provide information required for the planning of a large high Reynolds number transonic cryogenic tunnel, a relatively small pressurized transonic cryogenic tunnel was built and placed into operation in 1973. Design features and operational characteristics of the pilot transonic cryogenic tunnel have been reported in reference 4. Some of the initial experimental results obtained in the pilot tunnel have been reported in references 5 through 14. As a result of the successful operation of the pilot transonic tunnel, it was designated a research facility, in late 1974, renamed the 1/3-meter transonic cryogenic tunnel, and is now being used for aerodynamic research as well as cryogenic wind tunnel technology studies.

A wind tunnel operating at cryogenic temperatures can be no exception to the rule that any general-purpose tunnel should be capable of being used for a wide variety of purposes, which, at the very least, should include the testing of pressure models and the testing of sting-mounted force models using an internal strain-gage balance. Since the ability to use conventional ambient-temperature wind-tunnel techniques in a cryogenic tunnel would be highly desirable, a series of experiments has been undertaken in the 1/3-meter transonic cryogenic tunnel to determine if conventional testing techniques can, in fact, be used when operating the tunnel at temperatures as low as 77 K (-320°F).

One of the first tests to be made in the 1/3-meter tunnel was designed with the dual purpose of (1) obtaining experience in a cryogenic wind tunnel with an electrically heated internal strain-gage balance, the accompanying sting, sting-support arc, and an accelerometer used to determine angle of attack; and (2) investigating any possible effects of cryogenic stagnation temperature on the aerodynamic characteristics of a configuration having flow characterized by a separation-induced leading-edge vortex. As reported in reference 3, similar tests have been made previously at Langley in a low-speed cryogenic tunnel with satisfactory results using a water-jacketed internal strain-gage balance and a simple angle-of-attack mechanism.

The specific test program devised to meet the dual purpose consisted of using a complete force-measuring system — balance, sting, sting-support arc, and angle-of-attack accelerometer — for testing a delta-wing model at both ambient and cryogenic temperatures. The problems encountered with the first configuration of the electrically-heated balance and delta-wing model and subsequent modifications to the balance and the model which eliminated the problems are described. The static aerodynamic characteristics of the delta-wing model are presented with particular emphasis on the comparison of the data obtained at cryogenic conditions with the data obtained at ambient conditions.

SYMBOLS

The aerodynamic data p[illegible]ted herein are referred to the stability axis system. The origin for these axes is the moment reference center as shown on the sketch of the model presented in figure 1.

$\bar{c}$	mean geometric chord, $2/3\ \ell$, m
C_D	drag coefficient, $\frac{\text{Drag}}{qS}$
C_L	lift coefficient, $\frac{\text{Lift}}{qS}$
C_m	pitching-moment coefficient, $\frac{\text{Pitching moment}}{qS\bar{c}}$
ℓ	model length, 0.1981m
M	free-stream Mach number
p_t	stagnation pressure, atm (1 atm = 101.3 kN/m^2)
q	free-stream dynamic pressure, $1/2\rho V^2$, N/m^2
$R_{\bar{c}}$	Reynolds number, $\frac{\rho V\bar{c}}{\mu}$
S	wing plan-form area, 0.01057m^2
T_t	stagnation temperature, K
V	free-stream velocity, m/S
α	angle of attack, deg

μ free-stream viscosity, $N\text{-}s/m^2$

ρ free-stream density, kg/m^3

APPARATUS

Tunnel

The 1/3-meter transonic cryogenic tunnel which was used for these tests is a single-return fan-driven wind tunnel with a slotted octagonal test section measuring 0.34 m from flat to flat. The cooling procedure developed for this tunnel consists of spraying liquid nitrogen directly into the tunnel circuit and utilizing the latent heat of vaporization of the liquid nitrogen and the sensible heat of the gaseous nitrogen to cool the tunnel structure and to balance the heat of compression added to the stream by the drive fan. As a result of this method of cooling, the test gas is nitrogen rather than air.* The tunnel is capable of operating at Mach numbers from about 0.05 to 1.3 at stagnation temperatures from about 77 K to 350 K at stagnation pressures from slightly greater than 1 atm to 5 atm. Design features and operational characteristics of the 1/3-meter transonic cryogenic tunnel are given in more detail in reference 4.

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*Since 1972, an extensive study has been made by Adcock and coworkers at Langley to evaluate any possible adverse real-gas effects on aerodynamic data taken in nitrogen at cryogenic temperatures. These studies have shown that for stagnation pressures up to at least 5 atmospheres the behavior of nitrogen at cryogenic temperatures can be considered to be the same for all practical purposes as the behavior of an ideal gas. Portions of the real-gas studies have been reported in reference 9.

Model

There were two primary considerations in the selection of the model geometry:

(1) Since the type of flow to be simulated was the leading edge separation induced vortex flow with vortex induced reattachment, a highly-swept delta wing with sharp leading edges was selected; and

(2) Since comparisons of ambient and cryogenic temperature results at the same Reynolds number required large differences in the tunnel stagnation pressure, a thick, diamond shape cross section was selected in order to avoid aeroelastic distortions that could affect the aerodynamic results.

A sketch of the delta-wing model which was used for these tests is given in figure 1. The model was machined from 17-4 PH stainless steel which was heat treated to condition H 1150-M. With this heat treatment, 17-4 PH can be used at temperatures as low as 77 K (-320°F). The model has a leading-edge sweep of 75°, is 0.1981 m long, and is 0.1067 m wide at the base. The surface of the model exposed to the airstream was aerodynamically smooth and, in order to assure freedom for any possible temperature effects on the boundary layer flow to occur, the tests were performed with free transition, that is, no transition strips were applied to the model.

Model-Support System

Shown in figure 2 is a sketch of the model-support system consisting of the sting, the supporting arc, and the drive mechanism used to change sting incidence. Materials of construction include type 316 stainless steel for the arc, type 17-4 PH stainless steel heat treated to condition H 1150-M for the guide wheels and guide-wheel pins, phosphor bronze (type 510 copper alloy) for the guide-wheel bearings, brass for the double-threaded drive rod, and type 347 stainless steel for the sting, drive-rod clevis, seal assembly, and brackets for the guide wheels and drive rod. A commercial V-ring seal made of rings of Teflon was used to seal the drive-rod penetration in the plenum wall. The system was driven through a right-angle drive by a reversible fractional-horsepower variable-speed gear-motor located in the ambient temperature and pressure environment outside the plenum. The drive system was operated without lubrication except for the double-threaded brass drive rod which was sprayed with a Teflon based dry lubricant before each series of runs.

The drive rod failed several times during the course of these tests. The system was originally designed to have the drive rod made of 347 stainless steel. However, prior to the first series of tests it was decided to make the drive rod of brass rather than 347 stainless steel in order to avoid possible gauling problems since both the threaded clevis connecting the drive rod to the arc and the threaded bracket at the plenum wall were made of 347 stainless steel. Unfortunately, the strength of the brass drive rod in torsion was slightly less than required. The basic cause of the failures appears to have been binding of the brass drive rod in the threaded stainless steel bracket at the plenum wall. An excessively long threaded portion in the bracket caused the drive rod to bind as temperature was reduced due to the different thermal expansion coefficients of the brass and the stainless steel. This basic problem was aggravated by the unsupported right-angle portion of the external drive which caused the drive rod to bend under high loads thus causing additional binding when the slightly bent rod was forced through the threaded bracket.

The problems experienced with the arc drive system are not fundamental and can be solved by straightforward engineering methods. Two new arc-drive systems have been designed for possible future use with the 1/3-meter tunnel. One keeps the drive motor outside the plenum and drives the arc through a simple spur gear engaging internal gear teeth machined into the inner segment in the arc. The second drives the arc through the clevis using an electrically-driven linear actuator located in the plenum. Both of the new systems are designed to avoid the problems encountered with the drive rod of the original system and are expected to operate satisfactorily over the entire range of temperatures.

Balance

The electrically heated internal strain-gage balance and the various modifications to the original design which were required for successful operation are described in the appendix.

The major conclusions that have been drawn from the results presented in the appendix are as follows:

Based on the limited tests with the present balance it appears that the concept of keeping the balance at ambient temperatures (≈ 300 K) during tests at cryogenic stagnation temperatures is a fundamentally sound approach. However, the concept of allowing balance temperature to vary with stagnation temperature should be investigated further since the absence of heaters and insulators on the balance would make possible a reduction in balance diameter for a given load capacity.

The total heat input to the balance at cryogenic temperatures is in the order of 40 watts. This modest heat flux through the model would not be expected to modify in any way the nature of the flow over the model.

An improvement in balance design, from the point of view of uniformity of temperature across the gaged portion of the balance, can be realized if a material of high thermal conductivity, such as beryllium copper, can be used in making the balance.

Based on experience with the present electrically-heated balance, it appears likely that future cryogenic wind tunnel balances can be designed with only two heaters, one on either side of the gaged portion of the balance.

Based on bench tests of the present balance-sting assembly, it is concluded that an insulator between the balance and the sting is not essential and can be omitted in future balance-sting systems if the sting is made from a relatively poor thermal conductor.

Incidence Accelerometer

A precision servo accelerometer, one of several built to NASA-Langley specifications by a commercial supplier, was mounted on the sting-support arc to measure sting incidence. The accelerometer was mounted in an insulated housing which provided the proper mechanical suspension for vibration isolation and allowed the temperature of the accelerometer to be maintained automatically at approximately 310 K by using an electric heater.

Initially, problems were encountered with failure of the accelerometer during ambient temperature tests which, in order to hold Reynolds number constant for the hot-cold comparisons, were made at high values of total pressures. These failures were caused by very high levels of high-frequency vibration transmitted to the accelerometer through the sting-support arc. However, with a relatively simple modification to the accelerometer suspension it was possible to isolate the accelerometer from the high-frequency vibration and achieve a completely reliable and trouble-free system.

DATA CORRECTIONS AND PRECISION

Considerations of Wall and Support Interference

The size selected for the delta-wing model was a compromise between the desire to have a model large enough to accommodate a fairly large and rugged balance and the desire to test a model of reasonable size compared to the size of the test section. The fact that the model is somewhat larger than would normally be tested in a tunnel of this size is of no particular concern since the main purposes of these tests were to determine if there are any serious problems or anomalous effects of testing at cryogenic temperatures on either the test equipment or the aerodynamic characteristics of the model. With respect to the aerodynamic characteristics of the model, it would be expected that any interference effects due to using an oversize model would be unchanged between ambient and cryogenic test conditions if both Reynolds number and Mach number remained constant. With respect to the effects of cryogenic operation on the test equipment, the size of the model or any size related interference effects are of no concern. Therefore, no corrections have been made to the data to account for wall-interference effects.

Similar arguments can be made with respect to the need to consider for these tests any adverse effects on the data due to sting interference. That is, sting-interference effects will not compromise the basic purposes of the test and therefore no attempt has been made to correct the data to account for the presence of the sting.

Corrections to Angle of Attack

Based on experience in the testing of two-dimensional airfoils in the 1/3-meter tunnel it is known that flow angularity is very nearly zero over the range of Mach numbers used for these tests. Both sting and balance bending corrections have been taken into account in calculating model angle of attack. These corrections become fairly large for the higher operating pressures. For example, at $M = 0.85$ and $p_t = 4.6$ atm, the combined sting and balance bending correction increases the nominal angle of attack of 6.46° to 7.25°. The increased strength of the sting at cryogenic temperatures has been calculated and found to reduce the sting bending by a maximum of 0.03° at the highest angle of attack. This second-order correction to angle of attack has not been made for these tests. However, the magnitude of this correction can become significant under certain test conditions and should always be evaluated and applied as a correction to angle of attack if necessary.

Corrections for Changes in Model Size With Temperature

In any tunnel which operates over a wide range of temperatures, the change in model size with temperature should be calculated in order to determine if the change in model dimension is sufficiently large to justify the inclusion of this temperature effect in the reduction of data. For example, when operating at 115 K, a given linear dimension of the 17-4 PH model is reduced by approximately 0.2 percent from its room temperature value. Thus, C_D and C_L, which are nondimensionalized with respect to linear dimension squared, will be in error by approximately 0.4 percent while C_m, which is nondimensionalized with respect to linear dimension cubed, will be in error by approximately 0.6 percent if the data taken at 115 K is reduced by using values of S and $\bar{c}$ determined at 293 K (68°F). Such a correction is significant. Therefore, the aerodynamic data have been corrected to account for changing model size with temperature using the thermal expansion data for 17-4 PH and assuming the model temperature to be equal to stagnation temperature.

Accuracy of Test Conditions

Since the purpose of these tests was to investigate the effect of cryogenic operation on the balance system as well as on the aerodynamics of the delta-wing model under conditions of constant Reynolds number and

Mach number, it was necessary to repeat the various combinations obtained at ambient conditions at greatly reduced values of pressure and temperature. The relatively large values of probable error do not reflect the accuracy of the basic pressure and temperature measuring instrumentation but rather reflect the ability of the tunnel operators to obtain the desired test conditions and hold them constant for the time required to make an α sweep at a given Mach number.

For the data presented herein, values of the probable error of the test conditions are as follows:

	Probable error
Stagnation pressure, P_t, atm	± 0.004
Stagnation temperature, T_t, K	
Tests at ambient temperature	± 3.6
Tests at cryogenic temperatures	± 0.4
Mach number, M	± 0.003
Reynolds number, $R_{\bar{c}}$	± 0.09 X 10^6
Angle of attack, α, deg	± 0.1

Accuracy of Aerodynamic Data

The probable errors of the balance components cannot be expressed as simple constants due to the wide range of dynamic pressure covered during these tests. The values of the probable errors of C_m, C_D, and C_L can be found from the following expressions

$$C_m^* = \pm\ 0.1/q$$

$$C_D^* = \pm\ 0.4/q$$

and

$$C_{L'}^{*} = \pm 0.04/q$$

where C_m^*, C_D^*, and C_L^* are the probable errors of C_m, C_D, and C_L respectively and q is the dynamic pressure in kN/m^2. The values of q are given for each Mach number-stagnation pressure combination in the table of test conditions in the following section.

AERODYNAMIC TESTS

The aerodynamic tests were made at Mach numbers of 0.75, 0.80, and 0.85 at stagnation temperatures from about 114 to 300 K at stagnation pressures from about 1.2 to 4.6 atmospheres. Nominal values of stagnation temperature and pressure, dynamic pressure, and Reynolds numbers for the various Mach numbers were as follows:

Mach number, M	Stagnation temperature, T_t, K	Stagnation pressure, p_t, K	Dynamic pressure, q, kN/m^2	Reynolds number, $R_{\bar{c}}$
0.75	114.4	1.202	33.1	8.24×10^6
↓	297.3	4.600	127.6	8.25
0.80	114.4	1.196	35.8	8.52
↓	301.2	4.597	137.8	8.40
0.85	114.4	1.194	38.3	8.77
↓	302.8	4.616	148.6	8.62

Angle of attack was varied from about -1° to $+7^\circ$. (The nominal range of the angle of attack mechanism used for these tests is from -5° to $+15^\circ$. However, damage to the drive mechanism during the early part of these tests prevented the use of the full angle-of-attack range.) As previously mentioned, the surface of the model exposed to the airstream was aerodynamically smooth and no attempt was made to alter the nature of the flow by the addition of artificial roughness to the model.

DISCUSSION OF AERODYNAMIC RESULTS

The effect of test temperature on the static aerodynamic characteristics of the model is shown in figure 3 where C_m, C_D, and C_L are given as functions of α for Mach numbers of 0.75, 0.80 and 0.85. The aerodynamic data are presented in tabulated form in the tables at the end of the paper. By a suitable choice of stagnation pressures, it was possible to hold the Reynolds number constant at about 8×10^6 for both the ambient and the cryogenic temperature conditions at each of the three test Mach numbers. As can be seen, there is good agreement between the data obtained at ambient and cryogenic conditions. This good agreement indicates that flows with leading-edge vortex effects are duplicated properly at cryogenic temperatures and is further experimental confirmation of the prediction of reference 9 that cryogenic nitrogen should be a valid test gas at transonic speeds. It is, of course, necessary to assume that the balance was working properly in the cryogenic temperature environment as well as in the ambient temperature environment to interpret the aerodynamic data in this way. Such an assumption has been made in preference to the only alternate assumption possible, namely, the effects of temperature on the balance were equal and opposite to the effects of temperature on the aerodynamics of the delta-wing model.

CONCLUDING REMARKS

A sharp leading edge delta-wing model has been tested through an angle-of-attack range at Mach numbers of 0.75, 0.80, and 0.85 at both ambient ($\approx$300 K) and cryogenic ($\approx$114 K) temperatures in the Langley 1/3-meter transonic cryogenic tunnel. The results of this research and the conclusions drawn therefrom are as follows:

1. Agreement between the aerodynamic data obtained at ambient and cryogenic temperatures indicates that flows with leading-edge vortex effects are duplicated properly at cryogenic temperatures.

2. Accurate aerodynamic data can be obtained by using an internal strain-gage balance and conventional force-testing techniques if suitable measures are taken to minimize temperature gradients across the measuring sections of the balance and to keep the balance at ambient temperatures ($\approx$300 K) during cryogenic operation of the tunnel.

3. Based on the limited tests with the present balance it appears that the concept of keeping the balance at ambient temperatures ($\approx$300 K) during tests at cryogenic stagnation temperatures is a fundamentally sound approach.

4. The concept of allowing balance temperature to vary with stagnation temperature should be investigated further since the absence of heaters and insulators on the balance would make possible a reduction in balance diameter for a given load capacity.

5. In a cryogenic wind-tunnel, changes in model dimension with temperature can be significant and should therefore be considered in the reduction of data.

6. The total heat input to the balance at cryogenic temperatures is in the order of 40 watts. This modest heat flux through the model would not be expected to modify in any way the nature of the flow over the model.

7. An improvement in balance design, from the point of view of uniformity of temperature across the gaged portion of the balance, can be realized if a material of high thermal conductivity, such as beryllium copper, can be used in making the balance.

8. Based on experience with the present balance, it appears likely that future cryogenic wind tunnel balances can be designed with only two heaters, one on either side of the gaged portion of the balance.

9. Based on bench tests of the present balance-sting assembly, it is concluded that an insulator between the balance and the sting is not essential and can be omitted in future balance-sting systems if the sting is made from a relatively poor thermal conductor.

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APPENDIX

THE ELECTRICALLY HEATED BALANCE

As noted in the body of this paper, several modifications to the original electrically-heated balance were required for successful operation in the cryogenic environment of the wind tunnel. A description of the original balance and the various modifications that were made to it is given in this appendix. In addition, based on experience with the balance used for these tests, suggestions are given regarding the design of future balances for use in cryogenic wind tunnels.

Original balance design and initial testing.- In the development and use of the low-speed and transonic cryogenic tunnels at Langley, a philosophy has been adopted of maintaining, if possible, all transducers at near ambient temperatures ($\approx$ 300 K) in order to avoid problems with changes in sensitivity and/or zero with either changing average temperature of the transducer or temperature gradients within the transducer. In keeping with this philosophy, a three component electrically-heated internal strain-gage balance was designed and built especially for testing the delta-wing model in the 1/3-meter transonic cryogenic tunnel. The one piece balance, known as HRC-1, was machined from 17-4 PH stainless steel (vacuum remelt) which was heat treated to condition H 925. With this heat treatment 17-4 PH can be used under non-impact conditions at liquid nitrogen temperatures, that is, at temperatures as low as 77 K (-320° F). The balance was designed to have the following load limits:

Normal force. . . . . . . 890 N (300 lbf)

Axial force . . . . 89 N (20 lbf)

Pitching moment . . . . 1.37 N·m (20 ft-lbf)

At ambient temperature ($\approx$ 300 K) the balance accuracy is approximately $\pm$ 0.5 percent of the design load for all components. The balance is modulus compensated for ΔT = 55 K (100°F) and temperature compensated to 0.5 percent for ΔT = 55 K (100°F).

The balance was originally fitted with two 30 ohm resistance - wire heaters and two 50 ohm nickle resistance thermometer (NRT) temperature sensors. The temperature of the balance at or near a given heater is determined by the resistance of the NRT. In theory the temperature of the balance at an NRT is held constant by an automatic temperature controller which can vary the current through the heater in direct proportion to changes of resistance of the NRT with changes in temperature. Only two heaters should be needed to hold the temperature of the balance constant and to insure zero temperature gradient across the balance; one heater located at each end of the gaged portion of the balance. Such an arrangement has been used successfully for several years at Langley to eliminate problems caused by temperature gradients within dynamic-stability balances gaged with semiconductor strain gages. Thermal insulators made from glass-cloth reinforced epoxy were placed between the model and the balance and between the balance and the supporting sting in an attempt to reduce to an insignificant amount the conduction of heat from the balance to the stream through either the model or the sting. The balance as originally tested is shown in the sketch presented as figure 4 and in the photograph presented as figure 5.

The balance was first tested at cryogenic temperatures in the 1/3-meter tunnel in conjunction with a plastic model geometrically similar to the steel model used for these tests. The plastic model, however, did not have the cylindrical extension at the base of the model as shown in figure 1. During the tunnel cool-down process the balance temperature tended to follow the stream temperature and the desired balance temperature of 322 K could not be maintained at either the front or rear heater locations even when as much as 100 watts was supplied to each of the heaters. An analysis of balance temperatures as measured by the NRT's used for heater control and several copper constantan thermocouples located on the balance indicated that most of the heat from the front heater was flowing through the plastic insulator and model to the stream in such a way as to allow the front of the balance to be cooled. Also, it was apparent that a portion of the cold nitrogen stream was circulating over the rear of the balance and inside the sting cavity at the base of the model in such a way as to cool the rear portion of the balance.

Modification and re-testing.- In an attempt to rectify the problem at the front of the balance, the aft model mounting surface was modified to permit the addition of a heater and NRT sensor between the aft model mounting surface and the front of the gaged portion of the balance. In addition, the contact area of the forward mounting surface was reduced from 5.7 cm^2 to 3.4 cm^2 and the contact area of the aft mounting surface was reduced from 9.0 cm^2 to 1.5 cm^2 in order to reduce the conduction of heat from the balance through the model to the stream. The plastic insulator between the model and the balance was modified so that it made contact with the balance only on the surfaces indicated in figure 6.

In an attempt to solve the problem at the rear of the balance, a thin tubular insulating shield was machined from glass-cloth reinforced epoxy and was placed over the balance in such a way that it did not interfere with the balance reading but did prevent any direct contact of the cold stream with the balance. The balance as modified is shown in the sketch presented as figure 6.

As can be seen, the balance heater configuration is considerably more complex than the relatively simple concept of two heaters. In addition to a second heater at the front of the balance, heaters were added to each side of the axial-force measuring portion of the balance.

Before the modified balance was re-tested in the wind tunnel it was tested on the bench in a manner designed to simulate as closely as possible the extremely low temperature environment experienced by the balance in the wind tunnel. The model was mounted on the balance which in turn was mounted on the supporting sting. The model-balance-sting assembly was placed in a vertical position above an insulated bucket filled with liquid nitrogen. The heaters identified as 2 and 5 in figure 6 were used to establish a balance temperature of 322 K with near zero temperature gradient ($\Delta T < 0.5$ K) across the gaged portion of the balance. The assembly was then lowered until the model was completely covered with liquid nitrogen. The vertical position of the assembly was adjusted until the liquid nitrogen covered the rear surface of the model without pouring into the balance cavity. Even under this extreme condition heater No. 2 had no difficulty maintaining the front portion of the balance at 322 K. The model-balance-sting assembly was then inverted and immersed until the liquid nitrogen was in contact with the plastic insulator between the balance and the sting. Under this condition heater No. 5 had no difficulty maintaining the rear portion of the balance at 322 K.

Based on this experiment it is concluded that the plastic insulator between the balance and the sting is not essential and could be omitted in future balance-sting systems if the sting is made from a relatively poor thermal conductor. The fact that the sting was made from type 347 stainless steel, which has less than 5% the conductivity of copper at room temperature, limits the amount of heat that can be conducted from the rear of the balance through the sting to the cold stream whether or not the plastic insulator is present.

Of course, the bench test could not properly simulate the flow over the exposed rear portion of the balance or any induced flow of the stream into the balance cavity or possible flow through the sting wireway into the balance cavity. However, as a precaution against the latter possibility, the sting was heated and the wireway filled with paraffin wax.

Subsequent tests were made with both the balance temperature and the maximum test temperatures reduced to near 300 K in order to avoid melting the wax used to seal the wireway.

Wind-tunnel tests using the modified balance showed some improvement in the ability of the automatic temperature controllers to hold balance temperature, particularly at the front of the balance in the region of the model mounting surfaces. However, the rear portion of the balance still could not be held closely enough to the desired temperature. The resulting zero shifts due to the temperature gradient across the balance were of the order of three to four times the balance accuracy for the lift and pitching-moment components. Although it was possible to correct the lift and pitching moment data obtained during these tests for zero shifts by assuming both lift and pitching moment to be zero at zero incidence for the symmetrical delta-wing model, such a procedure is clearly impractical for arbitrary non-symmetrical models. Also, for the data obtained at cryogenic temperatures, the maximum balance loads were only about 20 percent of the balance capacity since the ambient temperature and cryogenic temperature tests were being made at constant Reynolds number and thus required only low total pressures at the low-temperature conditions. Thus, the "corrections" of 4 times the balance accuracy of ± 0.5 percent were equal to at least one-tenth of the indicated balance output, an unacceptably large correction even for symmetrical models.

Final modification and testing.- Two additional modifications were made to improve the situation at the rear of the balance. The first consisted of a simple change in the way the rear heating element was applied to the balance. The original rear heater consisted of resistence wire wound around the balance over a relatively thick insulating layer (epoxy with rice paper) which had been applied to the balance. The purpose of the insulating layer was to electrically insulate the heater from the balance. Unfortunately, it also proved to be an excellent thermal insulator. The presence of this insulating layer combined with the fact that 17-4 PH is a relatively poor thermal conductor, (roughly 5% the conductivity of copper) resulted in poor distribution of heat from the rear heater. To improve the distribution of heat a thin sleeve of beryllium copper, which is a relatively good thermal conductor, (roughly 10 times the conductivity of 17-4 PH) was fitted to the balance at the rear heater location. Also, a very thin insulating layer was used between the sleeve and the heater wire.

In addition to the changes made to the balance, a simple cylindrical extension was added to the model in order to further reduce the effects of the cold gas of the stream being circulated over the balance at the rear of the model. Such an extension, shown in figure 1, would, of course, in no way affect any hot-cold comparisons and, in fact, would not be expected to have a significant aerodynamic effect at all since it lies entirely in the wake of the basic delta-wing model. Additional justification for such a modification to the model in a development program such as this exists in the fact that the rear protion of a typical internal strain-gage balance is usually 8 or 10 sting diameters inside the model rather than projecting beyond the base of the model as was the case with the original model-balance combination.

During the subsequent wind-tunnel tests using the modified balance and model, the automatic heater controllers were able to hold the balance temperature constant at the heater locations under all test conditions. However, thermocouples located at various points on the balance away from the heaters did indicate the surface temperature of the balance was not being held at a constant temperature but in fact was as much as 20 K lower than the desired set-point temperature being maintained at the heater locations. The effect of the observed temperature differences on the balance surface did not, however, show up as a zero shift in any of the components of the balance. Because of the nature of the instrumentation being used it was not possible to get accurate values of the steady-state power being used by the heaters. However, it was possible to determine that the steady-state power never exceeded 10 watts for the front heater (No. 2) or 30 watts for the rear heater (No. 5).

The use of heater No. 1 at the extreme forward end of the balance was found to be optional. When in use, it would dissipate at most about 10 watts which reduced by 2 or 3 watts the amount of power dissipated by heater No. 2. Whether or not heater No. 1 was used did not affect the ability to hold the balance temperature constant across the gage section of the balance.

As determined by thermocouples located on the surface of the balance, the use of heaters No. 3 and 4 (figure 6) did result in a slightly more uniform distribution of temperature across the pitching-moment-normal-force measuring section at the rear of the balance. Unfortunately, no attempt was made to determine if the 5 watts or so dissipated by each of these heaters was critical to the successful performance of the balance or if, in fact, stable zeros for the various components would have been obtained without using heaters No. 3 and 4. In spite of the lack of experimental confirmation that the side heaters (Nos. 3 and 4) are redundant, it is very likely that they are at best only marginally beneficial with the present balance design. It appears, therefore, that future cryogenic wind tunnel balances could be designed with only two heaters (theoretically the minimum number), one on either side of the gaged portion of the balance.

The choice of material for balance construction is another area where some improvement is perhaps possible. In general, the avoidance of a temperature gradient across the gaged portion of the balance is made more difficult if the balance is made from a relatively poor thermal conductor such as 17-4 PH. An obvious improvement in balance design, from the point of view of uniformity of temperature, can be realized if a material of high thermal conductivity, such as beryllium copper, can be used in making the balance. (Beryllium copper has roughly ten times the thermal conductivity of 17-4 PH at room temperature.)

The heat input to the present balance seems remarkably small for such extreme tunnel conditions. Although some concern has been expressed as to the effect of heat flux through the model surface from a heated balance, such a modest heat flux through the model from the front heaters would not be expected to modify in any way the nature of the flow over the model. The aerodynamic data presented herein were obtained using the modified model and balance as shown in figure 7.

Toward the end of these tests, an attempt was made to determine if accurate aerodynamic data could be obtained if the balance temperature was held at some temperature less than ambient or, in the extreme case, was uncontrolled and allowed to follow stream temperature during cryogenic operation of the tunnel. By stopping the tunnel drive fan after tunnel temperature had been established and the model and balance allowed to come to temperature equilibrium with the stream, it was possible to take a "wind-off" zero reading and thus, hopefully, eliminate this potential source of error from the aerodynamic data. Unfortunately, the sensor used for control of heater No. 5 failed as the balance temperature was being reduced to 105 K (-100° F) so that only a limited amount of data was obtained.

The results are shown in figure 8 where C_m, C_D, and C_L are compared for constant test conditions ($M = 0.80$, $p_t = 1.2$ atm., $T_t = 114$ K) for balance temperatures of 310 K ($+100^\circ$ F), 255 K (0° F) and 114 K (-255° F). (The tabulated data are presented in table IV.)

Surprisingly good agreement between the data taken at the different balance temperatures was obtained for the drag component. The agreement is not so good for the lift component where there appears to be a shift in zero that was not taken into account by the cold wind-off zero. Although the model and balance were allowed to soak for several minutes at each new tunnel total temperature with the fan running in an attempt to insure uniform balance temperatures, the apparent zero shift is probably due to changing temperature gradients across the balance with time. The pitching moment component shows poor agreement with a constant offset at the higher angles of attack. Here, again, there appears to be a changing zero with time due to temperature gradients across the balance.

It should be possible, in theory, to operate a strain-gage balance in a cryogenic tunnel with no temperature control and by using calibration curves correct the data for changes in zero, changes in balance interactions, and changes in modulus. In practice it will probably be necessary to allow sufficient time between changing tunnel temperature and taking data for the temperature gradients within the balance to reach an acceptably small value. Depending upon the particular model-balance combination and the thermal characteristics of the balance, the required stabilization time may be unacceptably long and model-balance temperature pre-conditioning schemes may have to be evolved.

Based on the limited tests with the present balance it appears that the concept of keeping the balance at ambient temperatures ($\approx$ 300 K) during test at cryogenic stagnation temperatures is a fundamentally sound approach.

However, the concept of allowing balance temperature to vary with stagnation temperature should be investigated further since the absence of heaters and insulators on the balance would make possible a reduction in balance diameter for a given load capacity.

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TABLE 1. M = .75 DATA PRESENTED IN FIGURE 3A.

MACH NUMBER, M	STAGNATION PRESSURE, p_t, ATM	STAGNATION TEMPERATURE, T_t, K	DYNAMIC PRESSURE, q, kN/m^2	REYNOLDS NUMBER, $R_{\bar{c}} \times 10^{-6}$	ANGLE OF ATTACK, α, DEG	C_L	C_D	C_m
.755	4.601	301.6	127.9	8.12	.20	.0118	.0489	-.0025
.755	4.603	302.9	127.8	8.08	.02	.0070	.0486	-.0013
.752	4.593	300.0	127.0	8.15	-1.02	-.0159	.0485	.0037
.755	4.601	301.0	127.8	8.14	-1.03	-.0162	.0491	.0039
.756	4.604	294.5	128.1	8.39	.08	.0080	.0488	-.0016
.755	4.596	292.7	127.8	8.44	.08	.0080	.0488	-.0016
.754	4.602	299.4	127.6	8.19	2.25	.0627	.0510	-.0133
.756	4.602	298.1	128.1	8.25	2.28	.0632	.0518	-.0137
.754	4.603	300.3	127.7	8.16	4.47	.1243	.0591	-.0258
.755	4.610	301.9	128.1	8.13	4.43	.1266	.0588	-.0267
.749	4.606	305.4	126.6	7.96	6.70	.1997	.0731	-.0412
.750	4.606	306.1	126.8	7.94	6.69	.2010	.0737	-.0422
.758	4.604	299.5	128.5	8.22	.06	.0086	.0489	-.0016
.755	4.612	299.7	128.2	8.21	.05	.0089	.0488	-.0017
.765	1.216	113.3	34.2	6.54	-1.03	-.0182	.0525	.0058
.762	1.197	113.1	33.5	8.40	-1.02	-.0175	.0522	.0054
.736	1.200	116.8	32.2	7.87	.01	.0032	.0517	.0014
.746	1.201	114.8	32.7	8.15	2.10	.0570	.0544	-.0113
.753	1.207	114.4	33.3	8.28	4.06	.1103	.0608	-.0223
.754	1.200	114.1	33.1	8.26	6.21	.1782	.0734	-.0368
.753	1.196	114.1	33.0	8.24	6.21	.1772	.0735	-.0359
.758	1.196	114.6	33.3	8.21	.02	.0042	.0521	.0008

TABLE 2. M = .80 DATA PRESENTED IN FIGURE 3B.

MACH NUMBER, M	STAGNATION PRESSURE, p_t, ATM	STAGNATION TEMPERATURE, T_t, K	DYNAMIC PRESSURE, q, kN/m^2	REYNOLDS NUMBER, $R_{\bar{c}} \times 10^{-6}$	ANGLE OF ATTACK, α, DEG	C_L	C_D	C_m
.804	4.599	301.5	138.2	8.40	.11	.0083	.0516	-.0016
.806	4.593	304.7	138.4	8.28	-.96	-.0159	.0517	.0039
.806	4.597	299.9	138.4	8.46	2.42	.0646	.0545	-.0142
.801	4.606	306.2	137.7	8.23	4.45	.1263	.0620	-.0271
.796	4.601	304.6	136.6	8.25	6.69	.1993	.0763	-.0424
.804	4.585	289.9	137.6	8.80	.14	.0092	.0516	-.0018
.805	1.194	114.3	35.8	8.51	.02	.0061	.0528	-.0002
.803	1.196	114.6	35.8	8.49	-.96	-.0169	.0539	.0052
.807	1.197	114.5	36.0	8.52	.03	.0075	.0545	-.0005
.803	1.198	114.4	35.8	8.53	4.08	.1111	.0633	-.0225
.803	1.199	114.4	35.9	8.53	4.08	.1116	.0632	-.0232
.806	1.198	114.1	36.0	8.57	6.18	.1776	.0750	-.0374
.801	1.196	114.3	35.6	8.50	6.18	.1779	.0755	-.0381
.804	1.194	114.4	35.7	8.49	.04	.0081	.0537	-.0010

TABLE 3. M = .85 DATA PRESENTED IN FIGURE 3C.

MACH NUMBER, M	STAGNATION PRESSURE, p_t, ATM	STAGNATION TEMPERATURE, T_t, K	DYNAMIC PRESSURE, q, kN/m^2	REYNOLDS NUMBER, $R_z \times 10^{-6}$	ANGLE OF ATTACK, α DEG	C_L	C_D	C_m
.855	4.602	299.3	148.3	8.73	.07	.0107	.[illegible]549	-.0022
.856	4.605	309.9	148.6	8.35	.06	.0110	[illegible]551	-.0023
.853	4.624	300.5	148.7	8.72	-1.03	-.0144	.0549	.0038
.856	4.616	294.4	149.0	8.95	2.21	.0652	.0580	-.0145
.850	4.621	302.6	148.0	8.62	4.56	.1357	.0668	-.0304
.854	4.624	308.0	148.8	8.45	7.25	.2289	.0869	-.0513
.855	4.623	305.1	149.0	8.55	-.41	-.2685	.0594	.1185
.844	1.193	114.0	37.8	8.75	.04	.0063	.0566	.0003
.860	1.197	113.9	38.7	8.87	.17	.0079	.0563	.0001
.861	1.194	114.8	38.6	8.76	2.08	.0550	.0587	-.0115
.862	1.196	114.7	38.8	8.79	4.09	.1143	.0670	-.0249
.847	1.194	114.6	37.9	8.71	6.19	.1853	.0808	-.0413
.852	1.193	114.7	38.2	8.72	6.19	.1833	.0791	-.0402
.859	1.192	114.1	38.5	8.81	.03	.0075	.0558	-.0008

TABLE 4. M = .80 DATA PRESENTED IN FIGURE 8.

MACH NUMBER, M	STAGNATION PRESSURE, p_t, ATM	STAGNATION TEMPERATURE, T_t, K	DYNAMIC PRESSURE, q, kN/m^2	REYNOLDS NUMBER, $R_{\bar{c}} \times 10^{-6}$	ANGLE OF ATTACK, α, DEG	C_L	C_D	C_m
Balance at 310K								
.805	1.194	114.3	35.8	8.51	.02	.0061	.0528	-.0002
.803	1.196	114.6	35.8	8.49	-.96	-.0169	.0539	.0052
.807	1.197	114.5	36.0	8.52	.03	.0075	.0545	-.0005
.803	1.198	114.4	35.8	8.53	4.08	.1111	.0633	-.0225
.803	1.199	114.4	35.9	8.53	4.08	.1116	.0632	-.0232
.806	1.198	114.1	36.0	8.57	6.18	.1776	.0750	-.0374
.801	1.196	114.3	35.6	8.50	6.18	.1799	.0755	-.0381
.804	1.194	114.4	35.7	8.49	.04	.0081	.0537	-.0010
Balance at 255K								
.802	1.194	114.3	35.7	8.50	.01	.0111	.0494	-.0033
.812	1.197	114.3	36.3	6.57	2.02	.0568	.0538	-.0125
.811	1.195	113.9	36.2	8.60	4.13	.1165	.0604	-.0256
.813	1.203	114.6	36.5	8.59	6.19	.1880	.0702	-.0431
Balance at 114K								
.806	1.201	114.5	36.1	8.55	-.07	.0206	.0538	-.0087
.804	1.205	115.3	36.1	8.48	2.08	.0719	.0574	-.0212
.807	1.196	114.8	35.9	8.49	4.17	.1323	.0659	-.0354
.802	1.185	114.3	35.4	8.44	6.15	.1931	.0770	-.0483

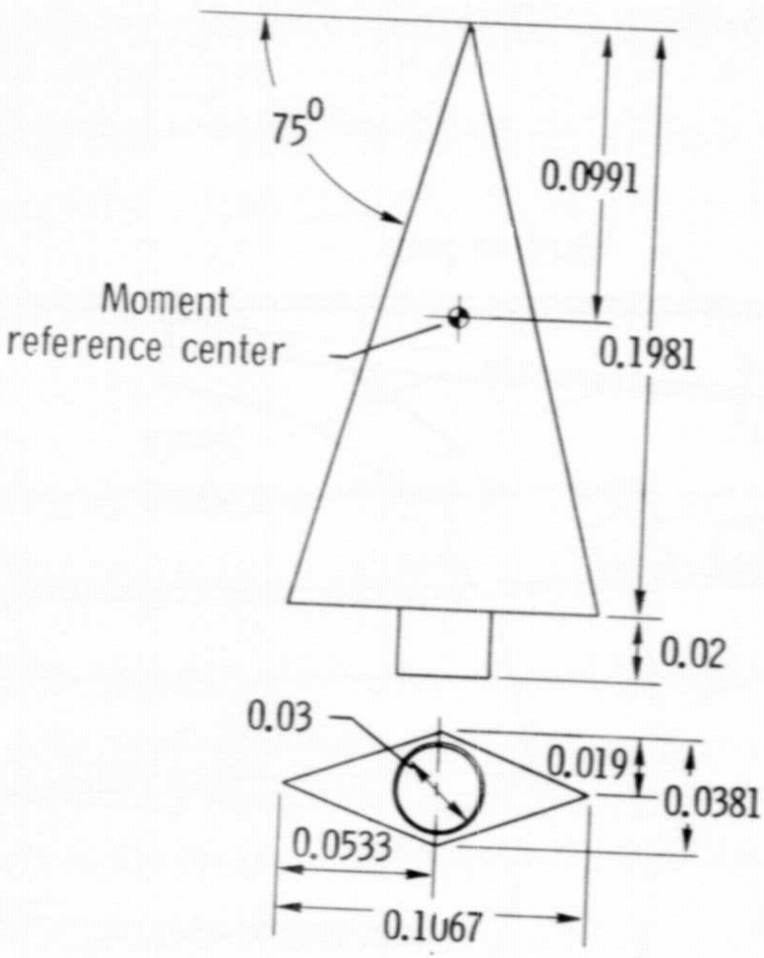


Figure 1.- Sketch of model. All linear dimensions are in meters.

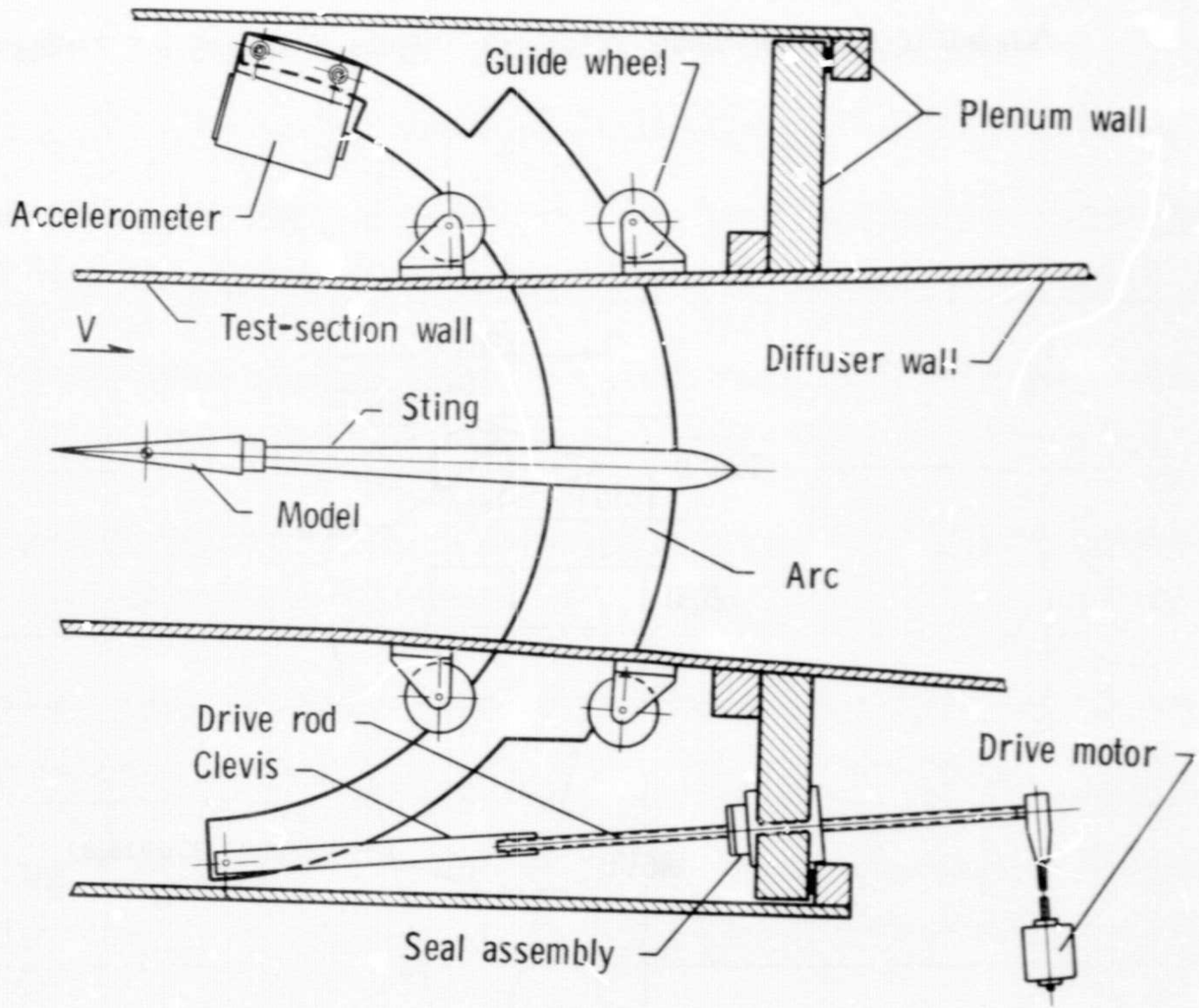
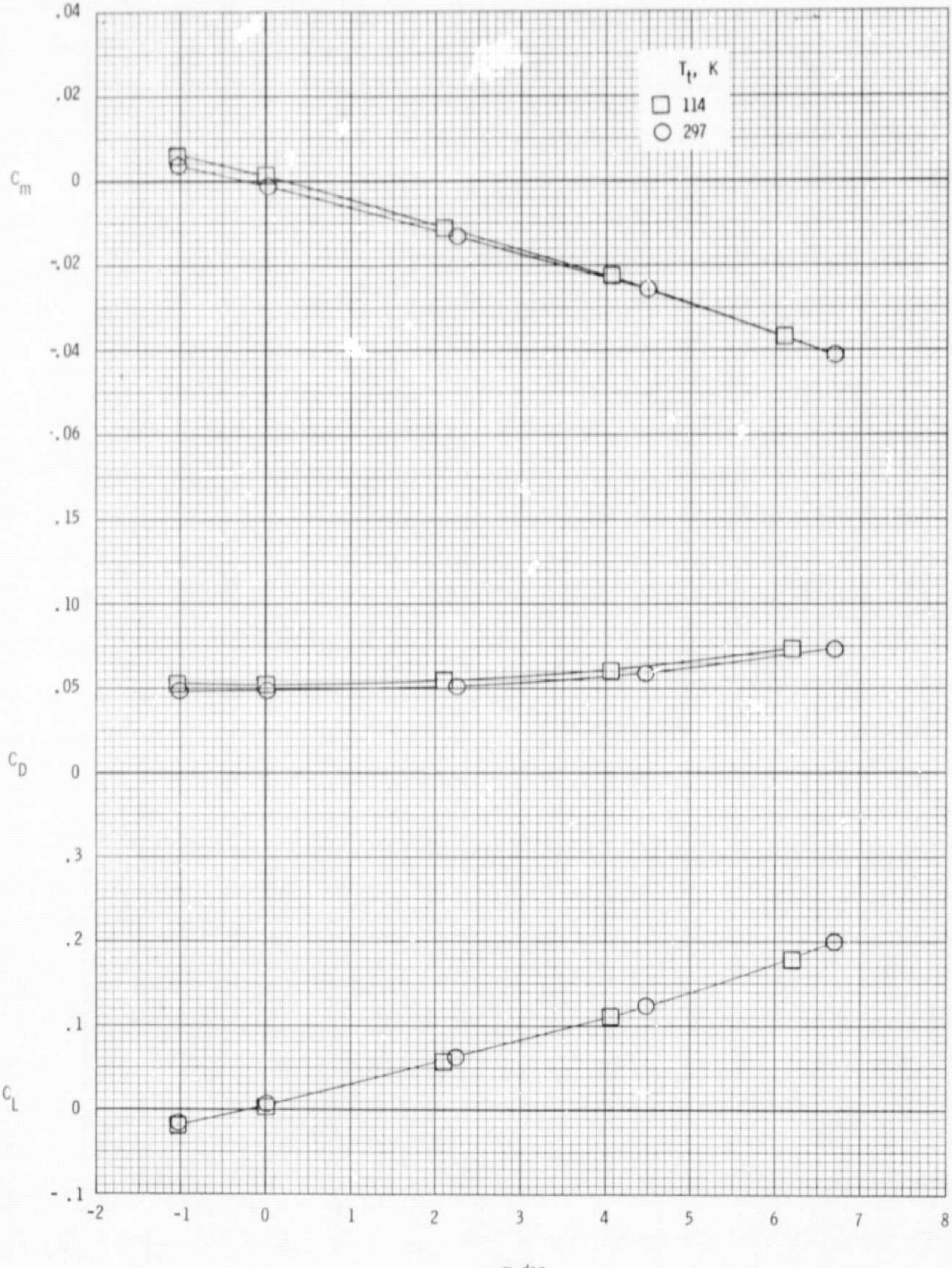
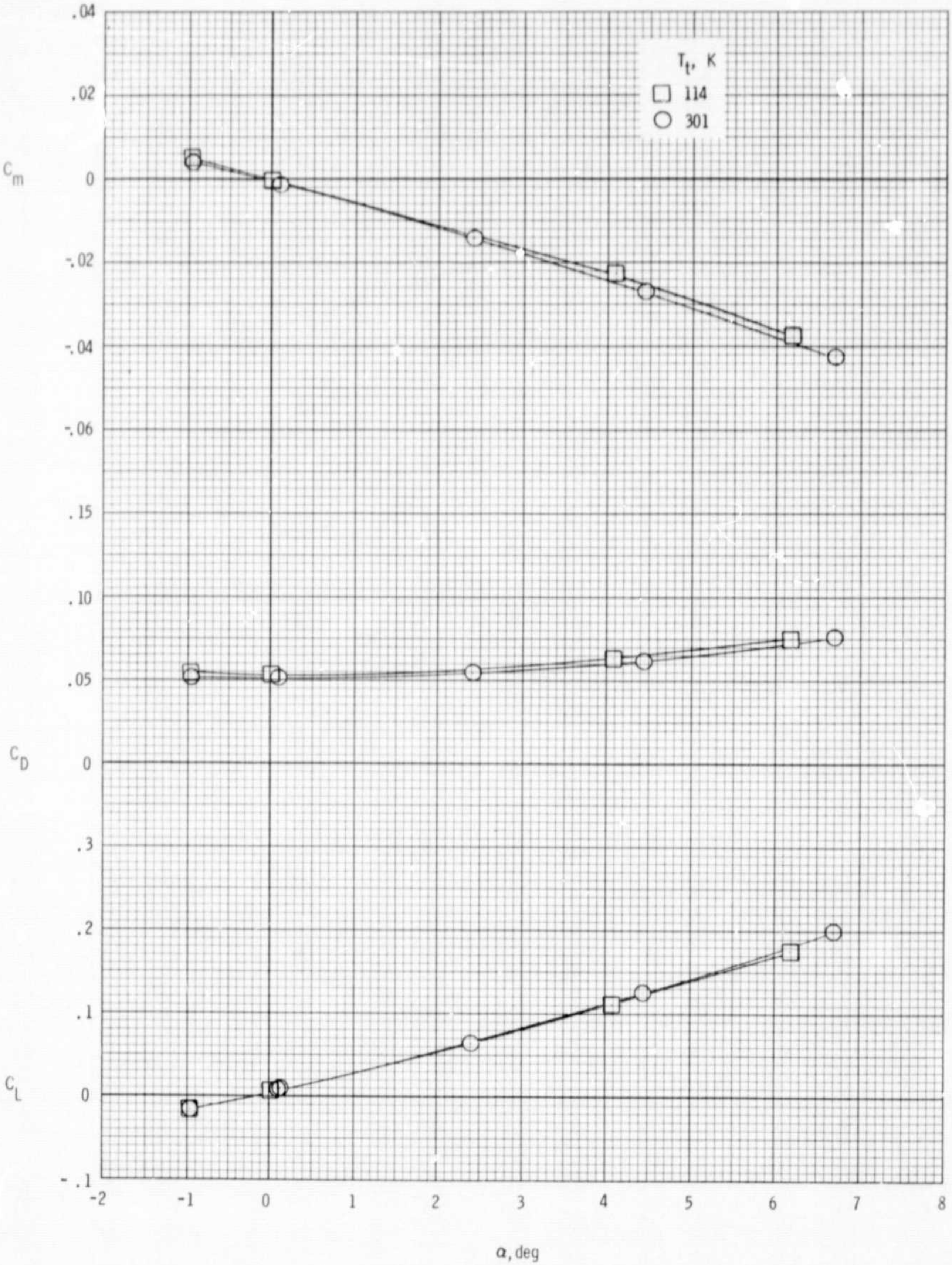


Figure 2.- Sketch of model-support system.



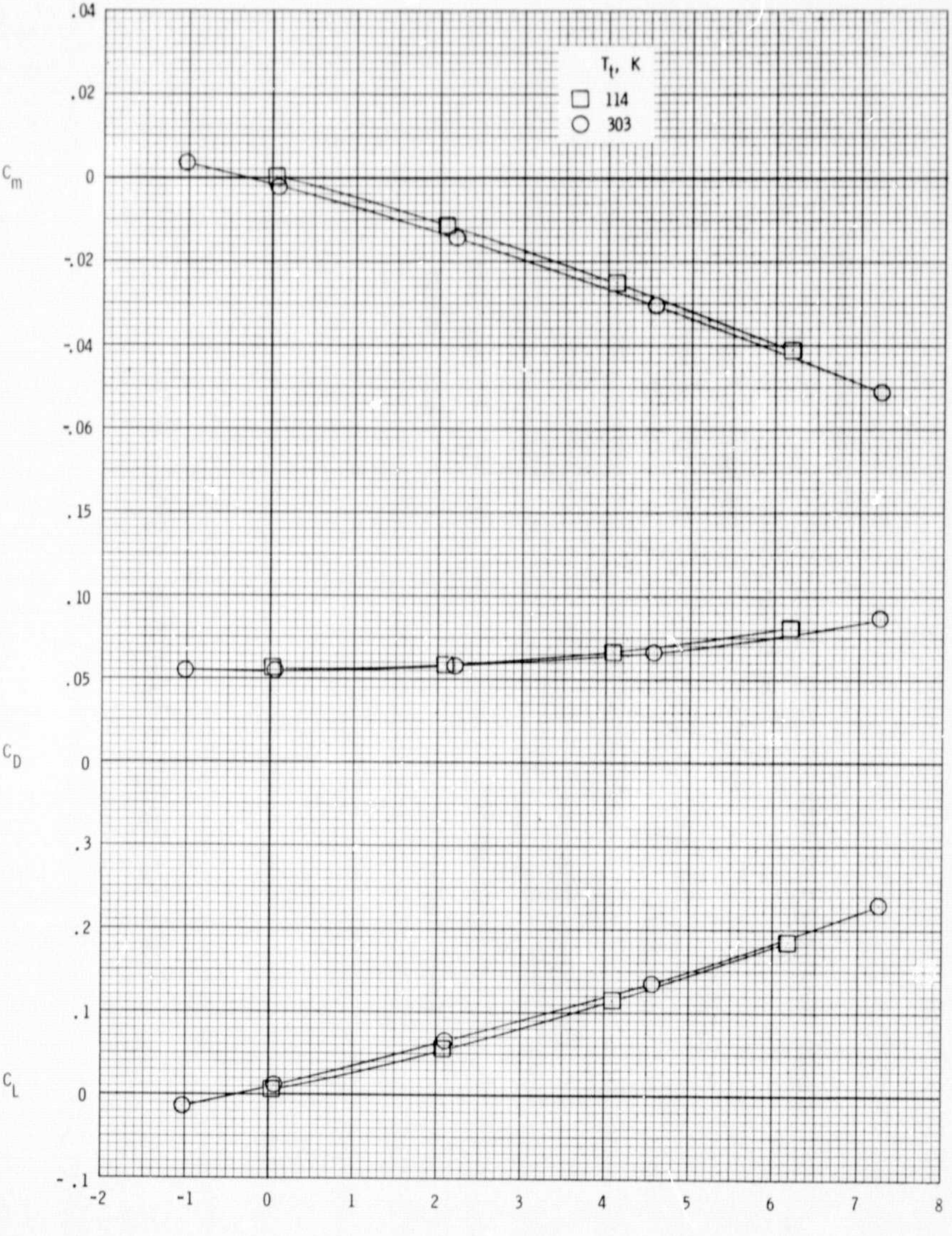
(a) M = 0.75

Figure 3. - Static aerodynamic characteristics of a delta-wing model at ambient and cryogenic temperatures as a function of angle of attack.



(b) M = 0.80

Figure 3. - Continued.



(c) M = 0.85

Figure 3. - Concluded.

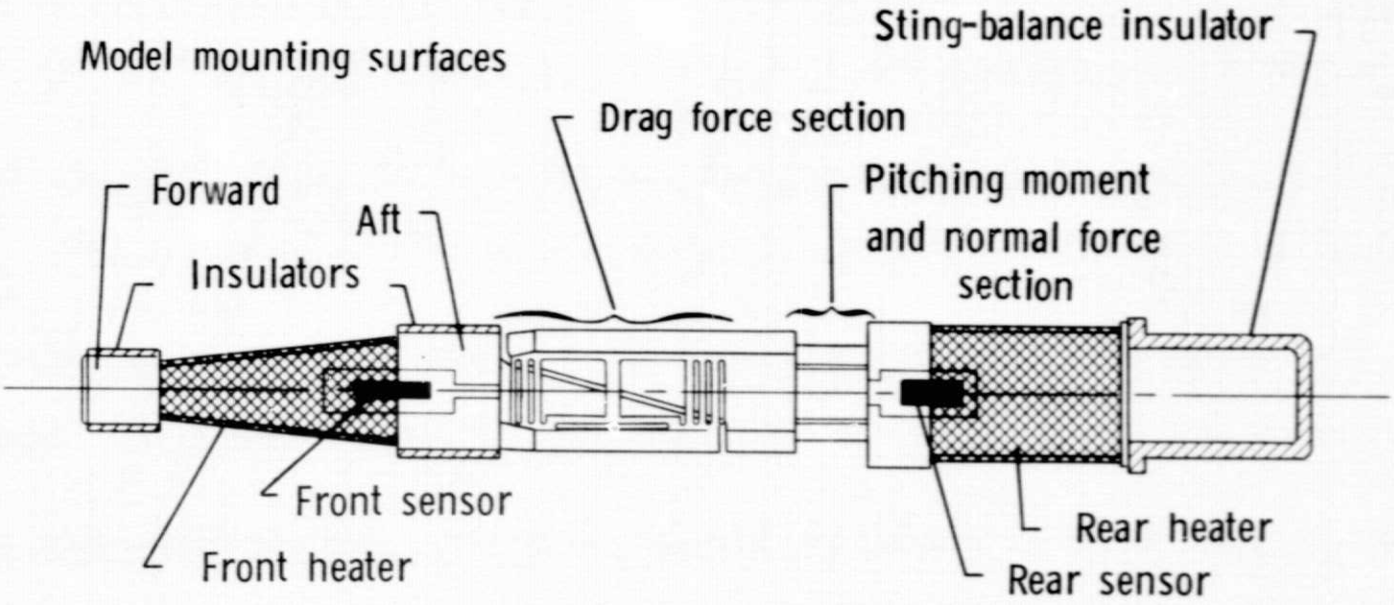


Figure 4.- Sketch of balance as originally tested.

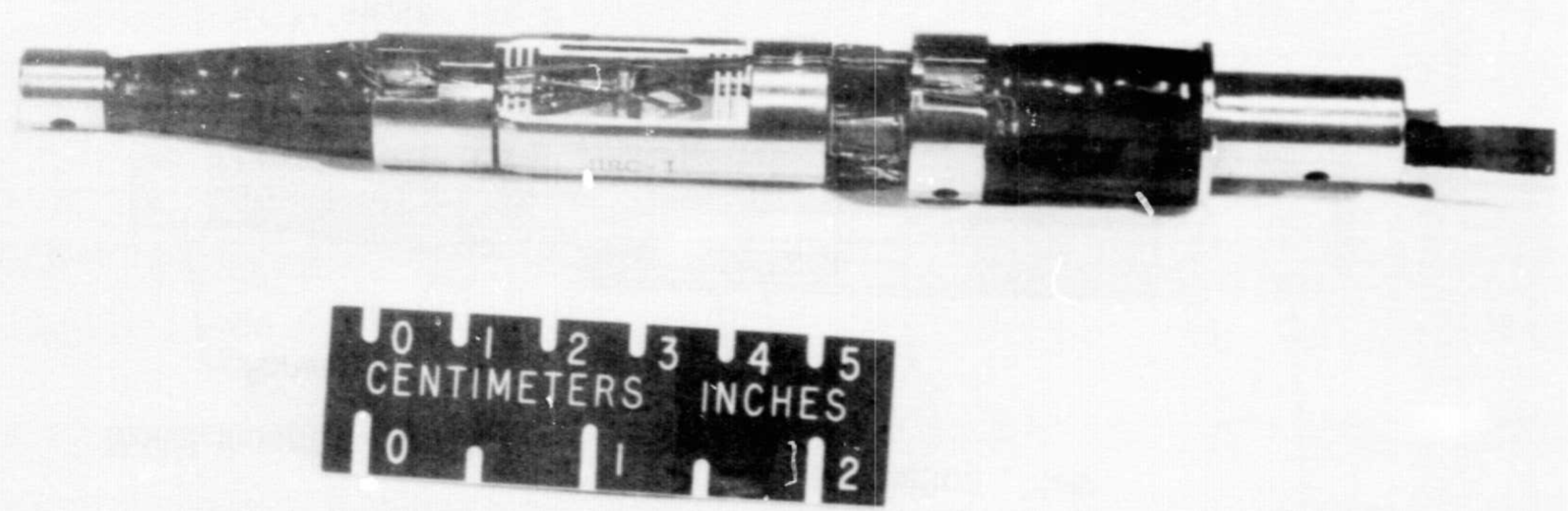


Figure 5.- Photograph of balance as originally tested.

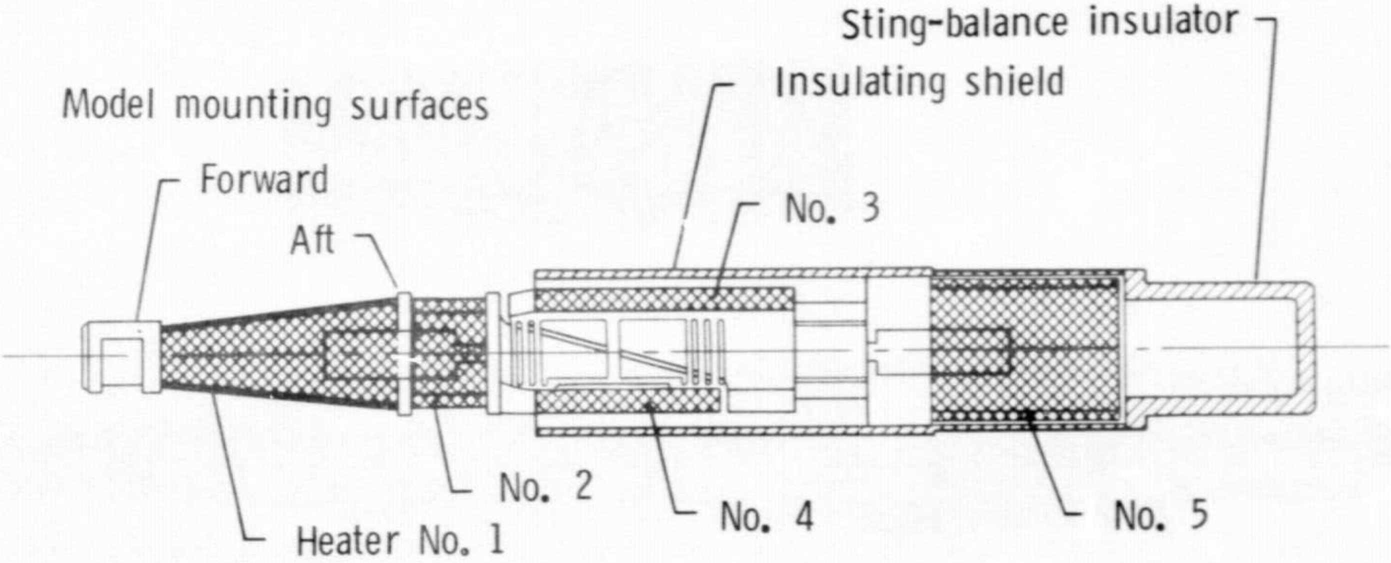


Figure 6.- Sketch of modified balance.

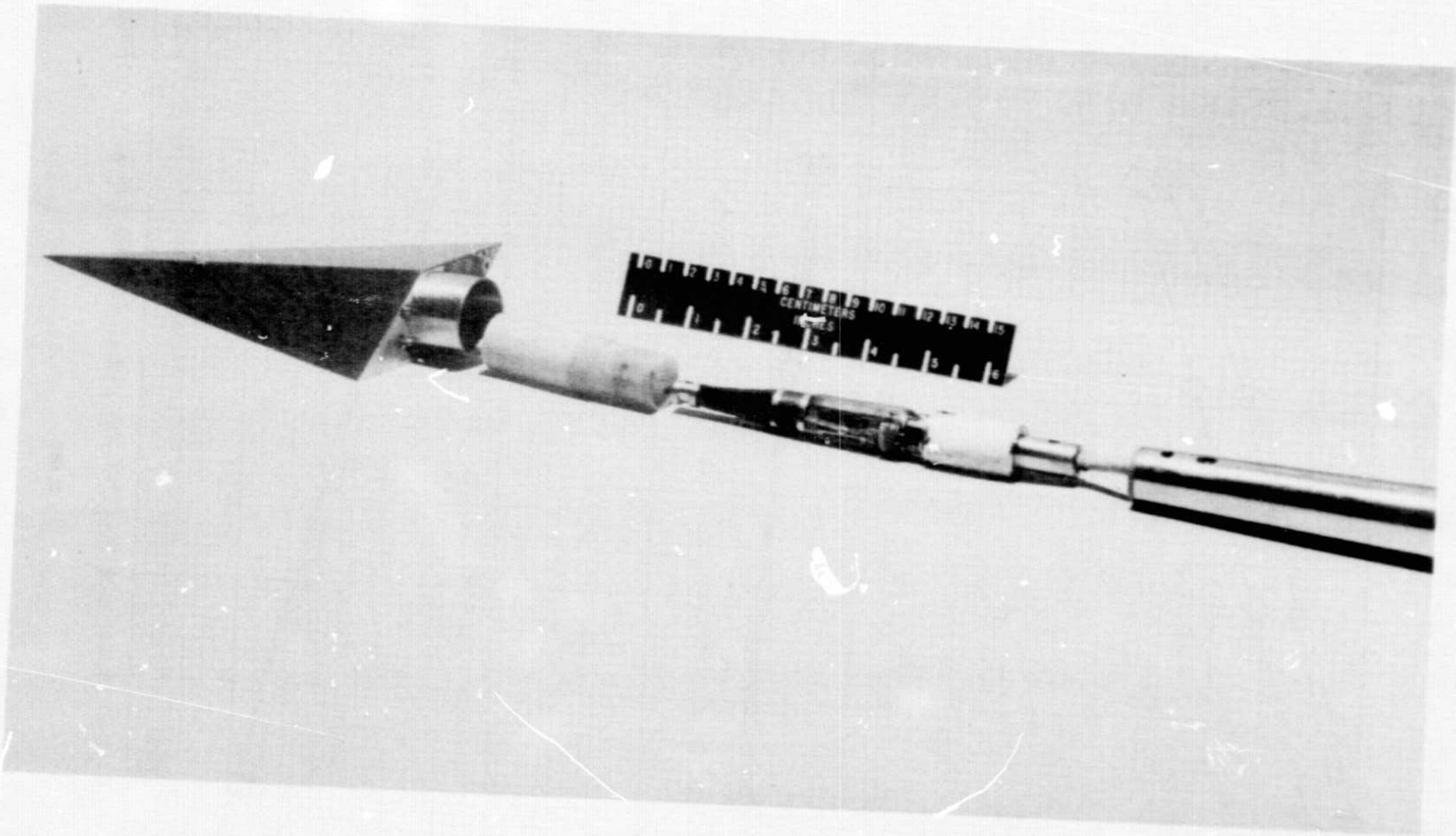


Figure 7.- Photograph of final configuration of model and balance.

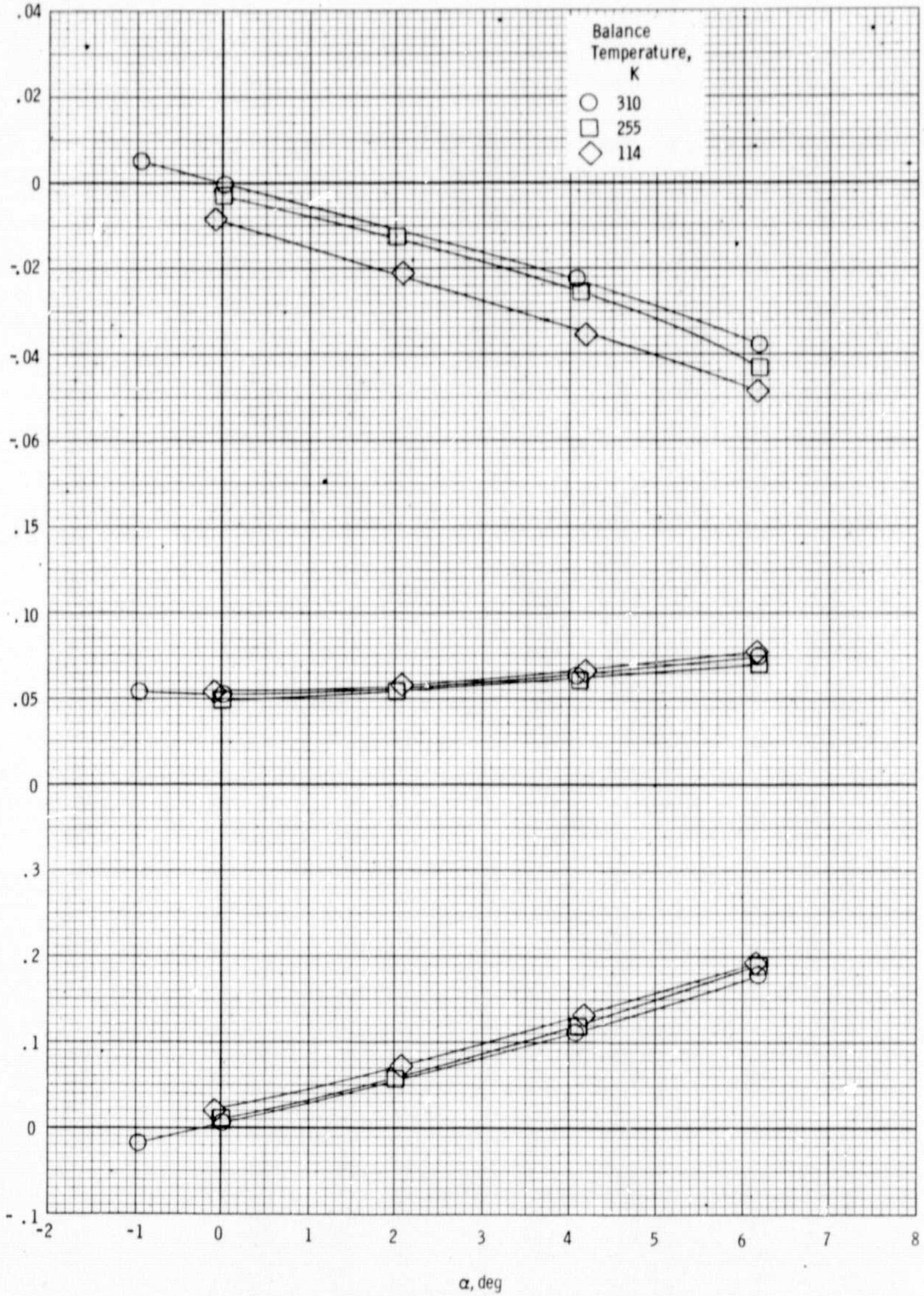


Figure 8. - Effect of balance temperature on aerodynamic data. $M = 0.80$, $P_t = 1.2$ atm, $T_t = 114K$.