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CRYOGENIC STRAIN GAGE TECHNIQUES USED IN FORCE BALANCE DESIGN FOR THE NATIONAL TRANSONIC FACILITY

SUMMARY

Techniques have been established for temperature-compensation of force balances to allow their use over the operating temperature range of the National Transonic Facility (NTF) without thermal control. This was accomplished by using a patented strain gage matching process to minimize inherent thermal differences, and a thermal compensation procedure to reduce the remaining thermally-induced outputs to acceptable levels. A method of compensating for mechanical movement of the axial force measuring beam caused by thermally-induced stresses under transient temperatures was also included.

INTRODUCTION

A force balance is a strain gage transducer used in wind tunnels to measure the forces and moments on aerodynamic models. Prompted by the decision to locate the NTF cryogenic transonic wind tunnel at Langley Research Center (LaRC), an extensive study program to determine the effect of cryogenic temperatures (down to -190^{o}C) on strain gage force balances was initiated in 1974.

When the cryogenic wind tunnel concept was first being evaluated at LaRC, force balances that had been designed for use in conventional wind tunnels (+20^{o}C to +80^{o}C) were used in pilot cryogenic wind tunnels using water jackets or electric resistance heaters to maintain normal instrument temperature while tunnel temperatures were reduced to as low as -190^{o}C (refs. 1 & 2). While the results of these "thermally-controlled balance" tests were encouraging, runs made that allowed the balance to follow tunnel temperature indicated the strain gages could function properly at cryogenic temperatures if thermally-induced outputs could be removed. Since balances could be made smaller (without heaters or insulators), less complex (no thermal control equipment), and more reliable (with fewer components) if thermal control could be eliminated, a study was undertaken to determine the thermally-induced effects and to develop methods of eliminating them. This paper presents the results of that study.

TESTS AND RESULTS

Thermal Effects

To obtain accurate force data over the large temperature range experienced in the NTF, it is necessary to eliminate or correct for the effects of any thermally-induced output so that the remaining output is a function of the applied load only. These thermally-induced outputs may appear as changes in the zero load output (apparent strain), in the output for a given applied load (sensitivity shift), and in the output due to mechanical deformation caused by thermal transients. Each element of the strain gage bridge was examined to determine its thermal characteristics in the temperature range of $-190^{\circ}C$ to $+70^{\circ}C$. These elements include: Base material, wiring, solder, moistureproofing, and strain gages. The first four elements will be discussed briefly followed by a more extensive discussion of the strain gage effects since the strain gages are the measuring element and have the most significant response.

Base material.- A maraging, high quality, 18-percent nickel, vacuum-remelt, stainless steel was chosen as the base material for its low hysteresis, high strength, and acceptable cryogenic properties in impact strength, fracture toughness, and dimensional stability. It has a coefficient of linear expansion of 10×10^{-6} in./in./$^{\circ}C$. Thermal expansion and contraction can induce apparent strain since strain gages cannot distinguish load strain from thermal strain. However, in a four-active-arm Wheatstone bridge, as is used on force balances where two arms are placed so they produce positive output in tension and two are placed so they produce positive output in compression, the apparent strain produced in each tension gage is cancelled by the apparent strain of a compression gage. For complete cancellation, it is necessary for each gage to have the same thermal response characteristics and for all four gages (or at least each tension-compression pair) to follow any temperature changes simultaneously. These points will be covered later. The base material modulus also increases as the temperature is lowered resulting in reduced strain with the same applied load, causing a decrease in output with load (sensitivity shift). (See reference 3.)

Wiring.- The silver-clad copper wire with TFE Teflon insulation used on conventional balances was found to be satisfactory for cryogenic use. Its change in resistance with temperature is nearly linear over the entire temperature range and, for the gage of wire used on a force balance, is usually negligible compared to the resistance change of the bridge. Even so, care is taken to keep equal length wire in each arm of the bridge, so even small resistance changes will cancel when placed in tension-compression arms. A small thermocouple effect (.009 $\mu V^{\circ}C$) was found in wire that came from a particular spool. While this was considered highly unusual and unlikely, one should be aware that this is an effect that can be present. Since the thermocouple effect is repeatable, in most cases if it is present its effect will not be isolated but be compensated for as part of the total temperature response during the thermal compensation procedures that will be discussed later.

Solder.- A solder recommended for cryogenic use by a strain gage manufacturer is composed of 93 percent lead, 5.2 percent tin, and 1.8 percent silver. However, its high melting point ($299^{\circ}C$) makes it very difficult to use.

The solder used on conventional balances tends to crystallize when subjected to cryogenic temperatures but the addition of antimony prevents this crystallization (called tin disease). Therefore, the solder chosen to be used for cryogenic applications is a commercially available solder that contains 63 percent tin, 36.65 percent lead, and 0.35 percent antimony with a melting point of 183^{o}C. Thermally-induced output problems were not observed when using this solder.

Moistureproofing.- The strain gage is encapsulated and is moisture resistant. However, the temperature compensation wire and solder joints are exposed making them vulnerable to moisture and possible shorting. The application of conventional moistureproofing compounds over the strain gage grid caused large, erratic apparent strain shifts at temperatures below -40^{o}C. When moistureproofing was applied only to the exposed solder joints and wire, there were still small output discontinuities and sometimes nonlinearities induced that were not there before moistureproofing. A number of moistureproofing compounds were tested. Those that worked best were M-Bond 43 (an adhesive and moistureproofing agent), an epoxy available from Micro-Measurements, Inc., and M-coat B (a nitrile rubber compound) also available from Micro-Measurements. These compounds still produced some thermally-induced apparent strain output. A better moistureproofing scheme was found while researching methods of protecting the balance surface from corrosion. The balance material, a maraging 18-percent nickel stainless steel, corrodes when exposed to moisture and the natural acids and oils found on the hands. The completely gaged and wired balance was protected by being dipped in a Teflon fluorocarbon dry lubricant, sprayed with a TFE Teflon coating, and then cured at 93^{o}C for durability. The strain gage grids are masked off during this procedure. This Teflon coating not only protects the balance surface from corrosion but was found to be satisfactory to keep moisture from penetrating to uninsulated portions of the strain gage bridge (provided the balance is purged with dry air or nitrogen while it is below the dew point during the warm-up cycle of any cold testing). The Teflon coating can be removed by washing with a solvent whenever it is necessary to perform electrical repair work or surface inspections.

Strain Gage.- As might be expected, the strain gages are the elements most sensitive to thermal changes. To minimize thermally-induced output, the gages must be: (1) selected to best match the base material on which they will be mounted, (2) located so they will not be subject to large thermal differences from gage to gage in the same bridge, (3) matched for similar thermal response characteristics, and (4) compensated as a bridge unit to eliminate residual thermal effects. Each of these procedures will be discussed.

(1) Gage selection: Commercially-available strain gages are made from a variety of alloys for different applications. The modified Karma gage is used on conventional balances and is a good choice for cryogenic applications since it has a relatively flat thermal response over a large temperature range and offers a choice of self-temperature-compensation (S-T-C) numbers that allow optimization of gage factor and apparent strain response to temperature (see figure 1). For a given "melt" or "lot" of alloy from which the gages are made, heat treatment determines the resultant S-T-C number.

However, gage factor and apparent strain cannot be changed independently for a given S-T-C number. The gages with S-T-C numbers from 11 to 13 were chosen for cryogenic use, with the S-T-C 11 having the least apparent strain shift on the chosen base material over the NTF operating temperature range and the S-T-C 13 for gage factor change most nearly opposing the modulus change to minimize balance load sensitivity changes with temperature. The SK 11 gage was a special-order gage made to LaRC specifications. The data on gage factor change due to temperature was not supplied but would be expected to fall between the SK 09 and SK 13 curves on figure 1.

(2) Gage location: To minimize the effect of temperature gradients, the gages should be located where the temperature gradient is minimized between gages. From figure 2, it can be seen that one end of the force balance is attached to the aerodynamic model, and the other end is attached to the tunnel support (sting). When there is a temperature change in the wind tunnel, the balance is heated or cooled more quickly at the ends (through conduction from the model and sting) than in the middle (by convection and radiation). A temperature gradient is more likely to develop along the longitudinal axis of the balance than in the lateral directions except in the axial section which will be discussed later. Generally, the measuring beams in a one-piece force balance are designed to deflect in simple bending; therefore, for maximum output, the bridge would be located with two tension gages on one side of the beam and two compression gages at the same longitudinal station on the other side of the beam. In this configuration, all four gages will be near the same longitudinal station on the balance and should experience the same temperature under both transient and steady state conditions. To improve upon this idea one step further, one gage on each side is turned perpendicular to the axis of principal stress and now measures strain according to Poisson's ratio (for steel, strain lateral equals approximately 1/3 strain longitudinal). The bridge is rewired so there is now one tension and compression gage on each side of the beam. There is one-third less total bridge output for the same load; however, each tension-compression pair will be even closer to the same temperature during heating or cooling since they are adjacent gages. (See figure 3.)

An additional benefit is realized with this gage configuration. It was found that there was less sensitivity shift with temperature than before. Previously the sensitivity at -190°C decreased .8 to 1 percent from the room temperature sensitivity. With the Poisson ratio gage configuration bridge the sensitivity decrease was less than .3 percent.

(3) Gage matching: Even though the tension and compression gages are placed so they are exposed to the same temperature they must also have similar temperature response characteristics in order to minimize thermally-induced output. Small differences in individual thermal response can be additive to produce significant output errors. A test was conducted to determine how much error was associated with differences in individual gage temperature response. Sixteen gages were mounted in

the center of a 4 x 6 x 1 in. piece of maraging steel and placed inside a cooling chamber. A bridge completion circuit external to the test chamber was connected to each gage. The chamber temperature was lowered to -190^{o}C and then brought back to room temperature (approximately 45 minutes to cool, 30 minutes to warm up). The output of each bridge was sampled and recorded on a data system every 15^{o}C. Following the test the data was reduced, plotted, and stored on the data system. A typical plot of 16 gage outputs is shown in figure 4. The output under transient temperature conditions (with room temperature electrical zero subtracted) is plotted versus temperature. The test block was not moistureproofed, thus the test was terminated prior to reaching 0^{o}C to prevent shorting. The two end points (at -190^{o}C and 25^{o}C) are essentially steady state. After the test the output of each gage could be combined mathematically with three other gages in any combination. The mathematically-combined bridge output was examined for excessive thermally-induced errors of the three types: steady-state output difference at -190^{o}C, nonlinearity, and thermal hysteresis (loop).

Excessive steady-state thermally-induced output occurs when the four gages chosen for one bridge have large end-point differences. The best way to avoid this error is to choose four gages that have nearly equal thermally-induced output at -190^{o}C. Another method that is less desirable is to choose two tension-compression half-bridge pairs that have equal but opposite thermally-induced output, thereby cancelling when they are combined in one bridge.

In addition to the steady-state end-point differences, the slope of the curves is not identical for all gages. Combining gages with unequal thermal-response slopes causes the bridge output to be nonlinear with temperature.

Some of the gages have larger thermal hysteresis than others, as indicated in figure 4. That is, the output while going cold is not the same as the output at the same temperature while warming up. If the gages with unequal thermal hysteresis are combined into a bridge such that this response is additive, the bridge could have a large hysteresis error under transient temperature conditions.

To minimize the effects of these errors in cryogenic strain gage bridge applications, a method was devised to select gages according to their thermal characteristics before permanent installation. This was accomplished by temporarily bonding 16 gages to a test block of maraging steel with a cyanoacrylate adhesive (Micro-Measurements M-Bond 200) and making a temperature test while acquiring data at 15^{o}C intervals. The data system controller could test all combinations of four gages and list those that fell inside the operator-selected limit of end-point error, nonlinearity error, and thermal hysteresis error. Of the three types of error, loop is given primary consideration since at this time there is no method to externally compensate for it. After the best combinations were identified, the gages and test block were heated and held at 170^{o}C for 2 hours causing the temporary bonding adhesive to disintegrate so the gages can be removed without damage; then cleaned and stored as thermally matched groups of four.

(4) Bridge thermal compensation:

Nonlinearity compensation - In unmatched gages, second order nonlinear bridge output was as large as ±150 μV (±1.5 percent full scale). The matched groups that had acceptable thermal hysteresis were then examined for nonlinearity and found to fall within a range of ±20 μV (±0.2 percent full scale). A nonlinearity of ±0.2 percent full scale is considered acceptable. If the ±0.2 percent full-scale criterion cannot be met, the nonlinearity can be corrected using manganin wire in the Wheatstone bridge circuit since the coefficient of resistance of manganin wire is nonlinear between -50^{o}C and -190^{o}C. This correction, however, should be avoided if possible for the following reasons: (1) Manganin wire introduces large end point apparent strain shifts which must, in turn, be corrected by copper wire; (2) manganin wire is difficult to solder; and (3) the resistance of the manganin wire drastically changes the room-temperature electrical zero (bridge imbalance).

Apparent strain compensation - The residuals left after gage matching are thermally compensated so that the maximum deviation of any thermally-induced bridge output falls within ±0.25 percent of full scale throughout the temperature range. The thermal resistance coefficient of nickel wire is nonlinear in the cryogenic region, therefore cryogenic balances use copper wire instead of nickel wire for compensating the apparent strain output of the bridge. Since copper wire has less resistivity and resistance change with temperature than nickel, it requires longer lengths of small wire to compensate large end-point errors. Gage matching reduces the amount of compensation needed thereby keeping the length of copper wire for bridge compensation to a reasonable length for the space available.

Special axial thermal compensation - It was noted early in the cryogenic research program that the axial force component appeared to have a very large thermal hysteresis output (up to ±250 μV or ±5 percent full scale) under transient conditions. Using matched gages or even matching gages to give loops of the opposite sign did not alleviate this problem. Note that the axial section of a balance is mechanically very complex. (See figure 5.)

Thermal gradients along the length of the axial section were considered the most likely cause of the axial output. All balance tests were run with thermocouples permanently installed in three locations; the front measuring gage, the axial measuring beam, and the rear measuring cage. There was little correlation between the axial thermally-induced output and any combination of these temperatures. When the axial section geometry and mass distribution were considered jointly it was observed that thermal gradients inside the axial section, instead of along the entire length of the balance, could be responsible for the axial thermally-induced output. When the upper axial section between the fore and aft flexures has a different temperature gradient than the corresponding lower axial section between the fore and aft flexures, the axial section moves as a parallelogram to relieve thermally-induced stresses. This movement generates true strain which is sensed by the axial measuring beam. To test this observation, thermocouples were placed at the top and bottom of each set of flexures on one side as shown in figure 5. A temperature test was conducted from room temperature to -190°C, and back, while the flexure temperatures and the axial output were recorded by a data acquisition system. There was a strong correlation between the temperatures read from the thermocouples placed above and below the axial flexures and the axial output [$E_0 = K(T_1+T_4-T_2-T_3)$] which indicates that the output is proportional to the difference in the temperature differential across the two diagonals. Temperature-sensitive wire was placed at the four flexure locations such that the wire at locations one and four are in the same tension leg of the bridge and the wire at locations two and three are in an adjacent compression leg. The change in resistance of these sensor wires caused by the different temperatures at each location is equal and opposite to that generated by the axial bridge due to the thermally-induced deflection, thus automatically temperature compensating the transient temperature-induced output of the axial section. This procedure can reduce the axial output due to thermally-induced deformation from as much as two percent full scale error to less than one-half percent full scale error.

Final Temperature Calibration

After the balance has been temperature compensated, a final temperature run is performed and the data recorded by the data acquisition system. A second order fit is applied to any residual apparent strain output for each of the six bridges. These corrections can be applied by the wind tunnel data reduction program.

CONCLUSION

Four-active-arm strain gage bridges can be used without thermal control to accurately measure forces and moments in a cryogenic wind tunnel environment. In order to accomplish this the gages must be: (1) selected and matched for thermal characteristics, (2) applied using techniques and materials approved for cryogenic use, and (3) thermally compensated over the entire operating temperature range.

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2. Richmond P. Boyden, William G. Johnson, Jr., and Alice T. Ferris, December 1983, Aerodynamic Force Measurements with a Strain-Gage Balance in a Cryogenic Wind Tunnel. NASA TP-2251.

3. Tobler, R. L., May 1980, Materials for Cryogenic Wind Tunnel Testing. NBSIR 79-1624 (Available as NASA CR-165716.)

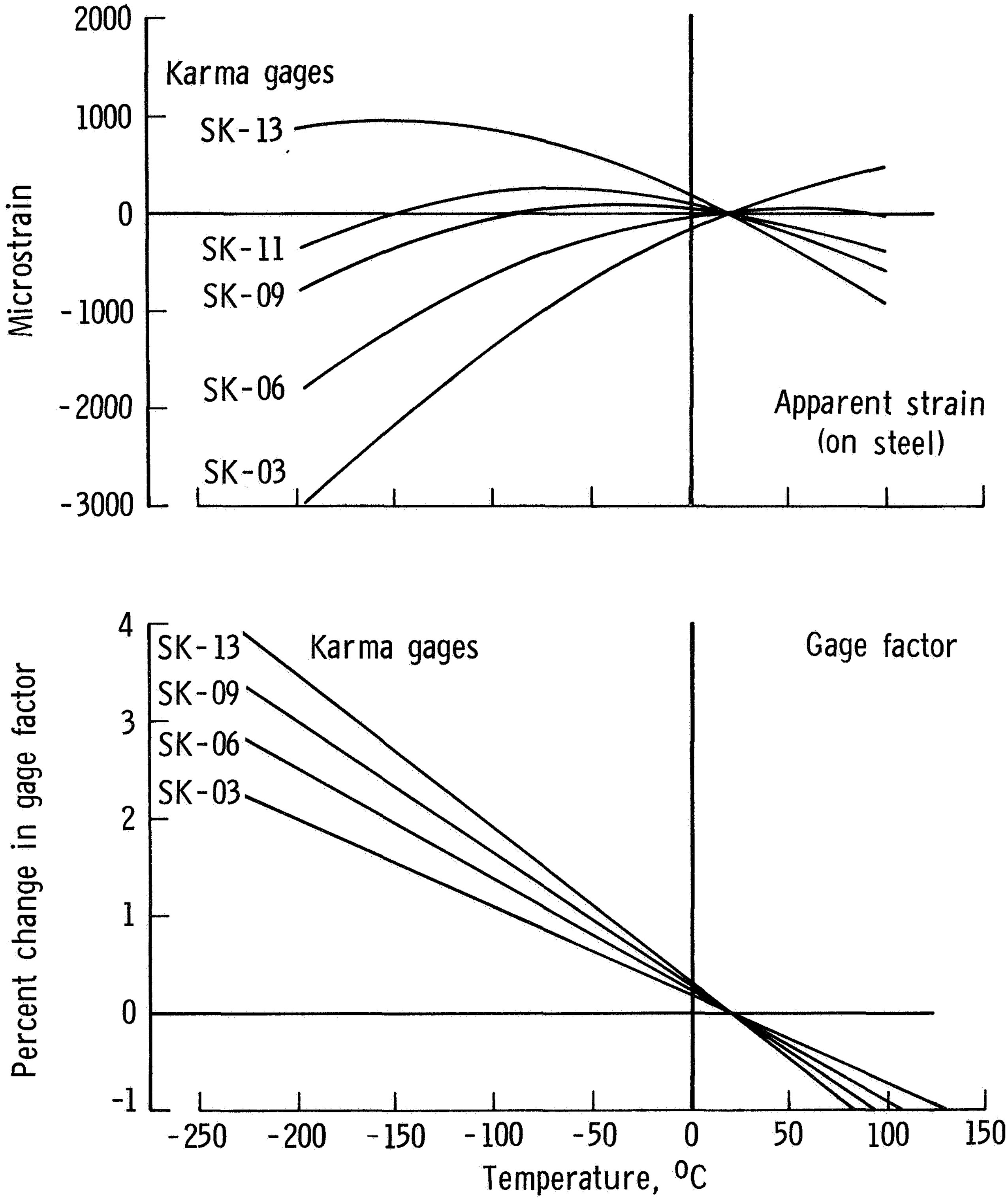


Figure 1. - Apparent strain and gage factor change with temperature.

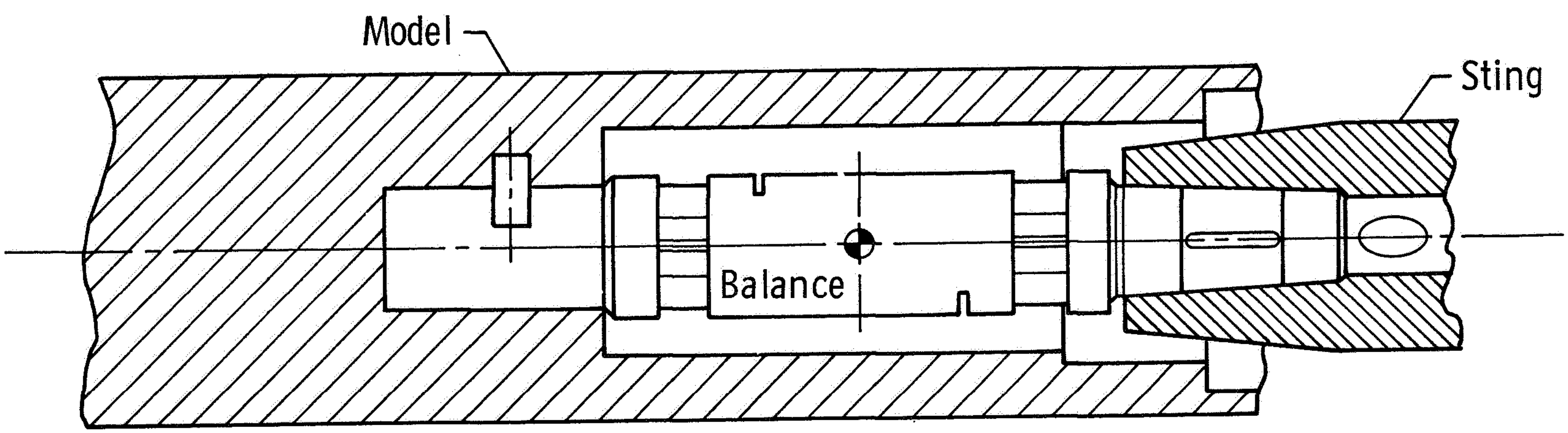
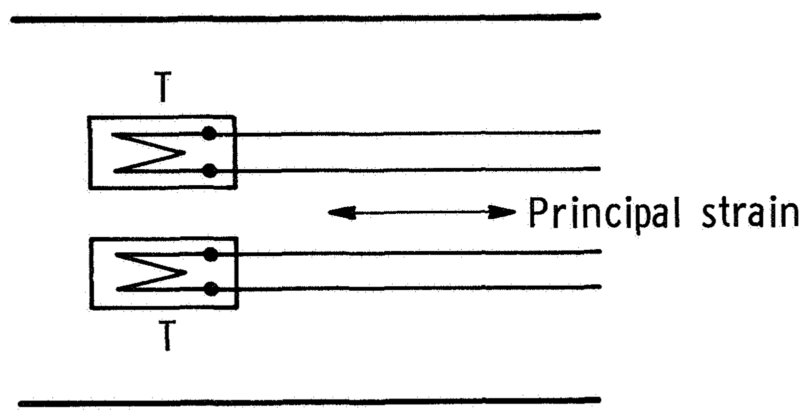
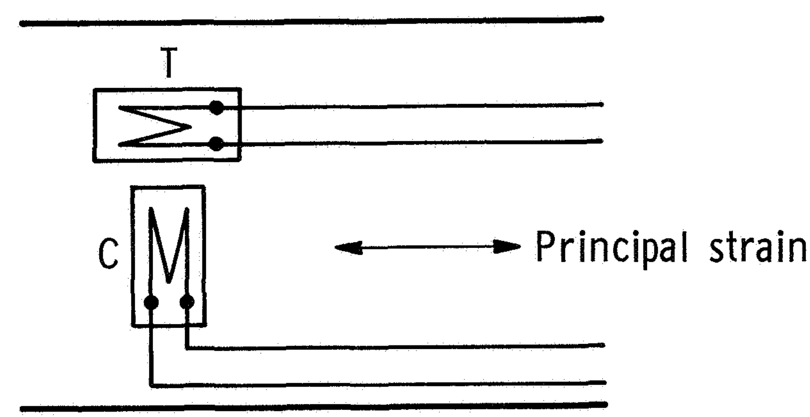


Figure 2. - Model-balance-sting configuration.



Principal Strain Configuration



Poisson Ratio Configuration

Figure 3. - Gage placement.

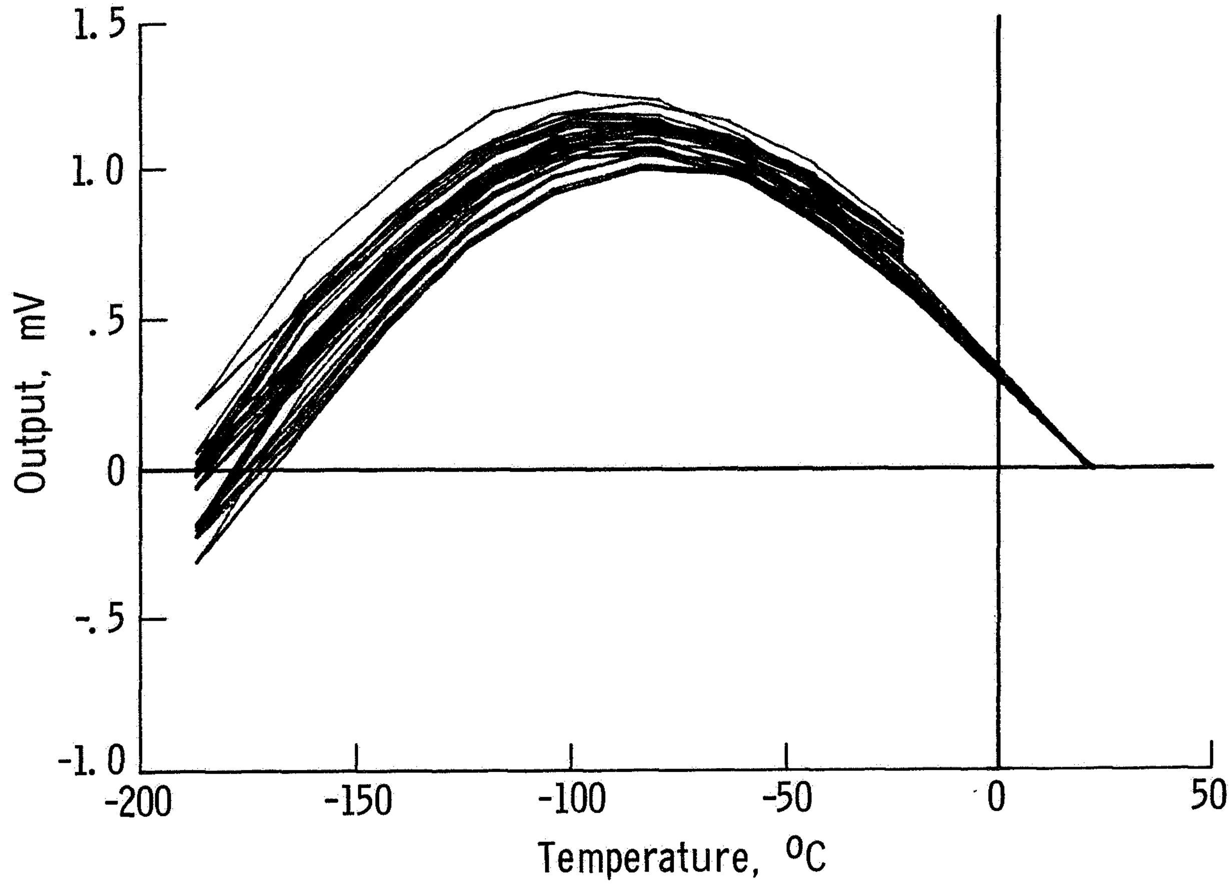


Figure 4. - Apparant strain curves of 16 SK-12 gages.

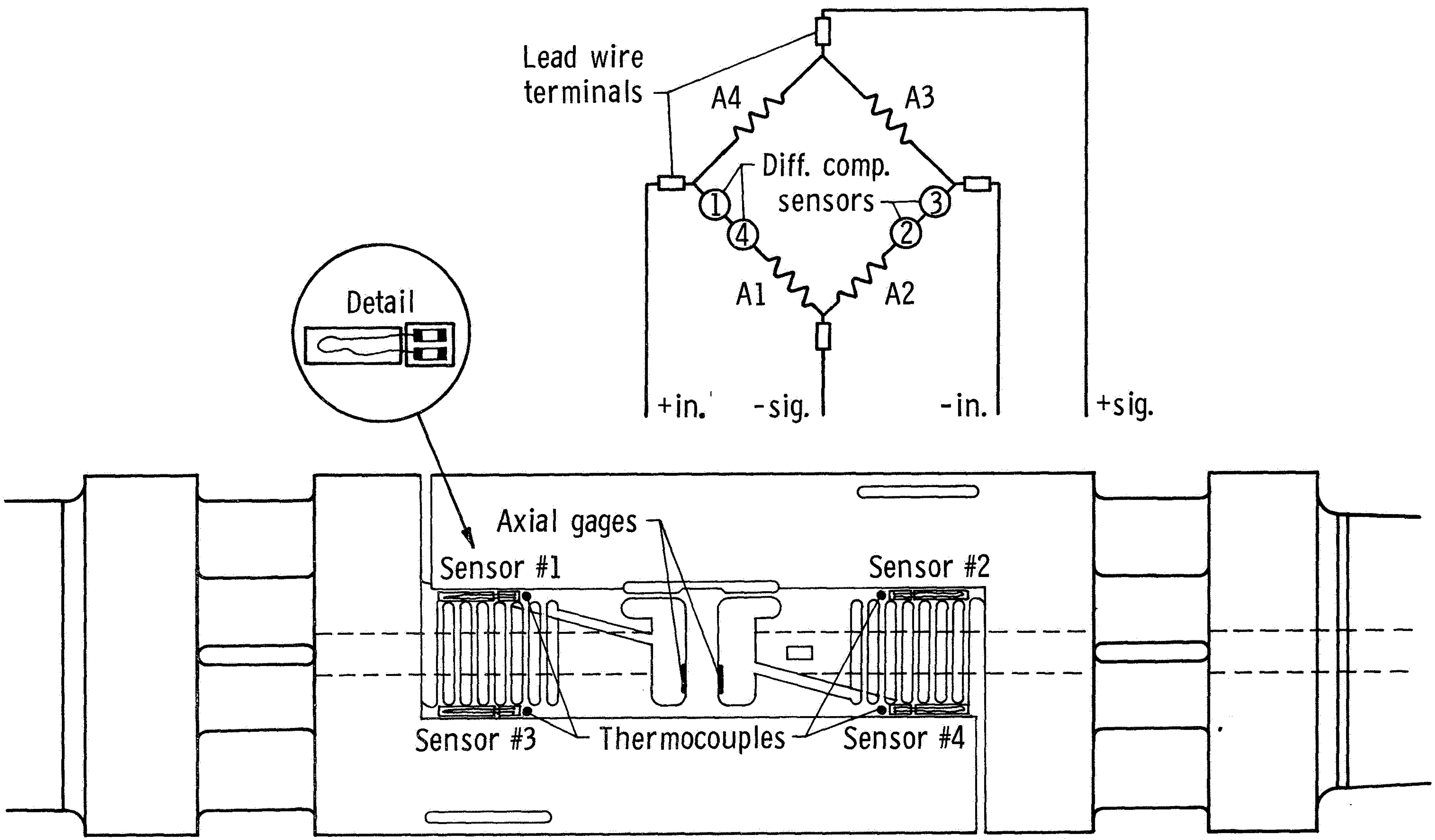


Figure 5. - Axial section.

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16. Abstract

A force balance is a strain gage transducer used in wind tunnels to measure the forces and moments on aerodynamic models. Techniques have been established for temperature-compensation of force balances to allow their use over the operating temperature range of a cryogenic wind tunnel (-190°C to 60°C) without thermal control. This was accomplished by using a patented strain gage matching process to minimize inherent thermal differences, and a thermal compensation procedure to reduce the remaining thermally-induced outputs to acceptable levels. A method of compensating for mechanical movement of the axial force measuring beam caused by thermally-induced stresses under transient temperatures was also included.

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