MEASUREMENT OF INTERNAL FORCES IN SUPERCONDUCTING
ACCELERATOR MAGNETS WITH STRAIN GAUGE TRANSDUCERS*

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BNL--41979

DE89 008158

MAR 7 4 1989

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An improved method has been developed for the measurement of internal forces in superconducting accelerator magnets, in particular the compressive stresses in coils and the end restraint forces on the coils. The transducers have been designed to provide improved sensitivity to purely mechanical strain by using bending mode deflections for sensing the applied loads. Strain gauge resistance measurements are made with a new system that eliminates sources of errors due to spurious resistance changes in interconnecting wiring and solder joints. The design of the transducers and their measurement system is presented along with a discussion of the method of compensation for thermal and magnetic effects, methods of calibration with typical calibration data, and measured effects in actual magnets of the thermal stress changes from cooldown and the Lorentz forces during magnet excitation.

Foreword

In current superconducting accelerator magnet design, it is recognized that the magnet coils should be well clamped and compressed to minimize conductor motion under the action of the Lorentz forces during magnet excitation. This tends to minimize or eliminate training and achieve a quench performance consistent with the short sample characteristics of the superconductor. The reliable measurement of the azimuthal coil stress (and longitudinal coil end forces, as well) is an important aid in evaluating and improving coil clamping systems in order to meet magnet performance requirements.

Although azimuthal pressure sensing gauges have been used for some time in accelerator magnet assemblies, there has not been much success in obtaining reliable readings of coil stress changes at operating conditions and under conditions of magnet excitation when it is important to know if the coils are still being held under compression. The problems with these previously used gauges have been basically attributed to two characteristics of their design:

1. The gauge design was typically a short bar acting in direct compression with a pair of gauges mounted on opposite sides of the bar as shown in Figure 1. Because of the necessarily small size of the bars, the gauges are mounted very close to the edges. In this case, edge effects and non-uniform loading may impair the compensation for bending effects and lead to erroneous measurements of stress. This made the transducers sensitive to the geometry of their mounting. Thus, the gauges could not be calibrated in direct compression and the same calibration used to determine the polar stress of coils when the gauges were mounted in the magnet.
2. The measurement procedure in this case used two active gauges and two compensating gauges for temperature and magnetic effects which were mounted in a full bridge configuration. Measurements of the resistance change with temperature of these and similar gauges in the same lot number show unequal resistance changes with temperature down to 4.2° K as shown in Figure 2. Thus, the bridge compensa-

tion would, in general, produce an apparent strain offset and thus an uncertain value of low temperature readings. For example, a typical resistance change variation from ambient temperature to ~4.5 K for gauges of the same lot would be .100 ohm. This is equivalent to an apparent strain of ~140 microstrain which is equivalent to ~4000 psi uncertainty in the value of the coil stress reading. The full bridge excitation method is also sensitive to errors induced by variations of the resistance of the leads with temperature and magnetic field as well as variations in the contact resistance of soldered joints.

The above deficiencies have been corrected with the beam type strain gauge transducer and measurement system that has been developed at BNL. The transducers, measurement system, method of calibration and test results are described below using the SSC dipole magnet as an example.

DiscussionThe Transducer Beams

Sensitivity to edge effects and non uniform loading have been significantly reduced with a beam type or bending mode transducer as shown on Figure 3. The beams are mounted in the SSC magnet collar packs with the compensating gauges as shown in Figure 4. In this case the gauge is mounted relatively far from the edge of the bar and thus sits on material that is uniformly strained when subjected to bending from the pressure of the coil on the opposite face of the beam. The beams have been designed to produce a deflection of about .001 inch when loaded with a coil at a pressure of 10,000 psi. A .125 inch strain gauge mounted at the center of the beam span would be in a relatively uniform strain field as shown in Figure 5 which is a plot of the longitudinal bending stress for one of these beams as a function of the distance from the center line. The potential for measurement errors from edge effects are thus avoided with this beam design. Another benefit of the beam design is improved sensitivity to mechanical strain relative to apparent strain effects. Thus, with the beam design a sensitivity about 4 times greater than that with the previously used direct compression gauges is obtained.

The Measurement System

Single element strain gauges are used which are excited with a constant current source of 2.5 ma in order to have a low self heating effect. The voltage across each gauge is measured by means of separate leads which carry no current. Thus, the measurement of the gauge resistance is not affected by variations in the lead resistance or solder joint contact resistances as long as the excitation current remains constant. Using this method, only one gauge is required to measure the applied pressure of the coil against the beam with a correction supplied by a compensating gauge measured with the same method. This four-wire gauge resistance measuring method is shown in Fig. 6a with the simplified block diagram of the measurement system shown in Fig. 6b. The system consists of a scanner, digital multi-meter, multi-channel current power supply, standard resistor and a control computer. The scan-

* Work performed under the auspices of the U.S. Department of Energy
Submitted to the 1988 Applied Superconductivity
Conf., San Francisco, CA, Aug.21-25,1988

net serves to multiplex the voltage signals from the gauges and routes them to the multi-meter. It also relays control signals to the power supply from the computer. The power supply has four each 2.5 ma output channels. Stability of the power supply is approximately .002% for one hour and .002% per degree centigrade. The scanner is controlled by the computer to turn the individual channels on and off at the time readings are to be taken. The digital multi-meter has both voltage and current measurement capability with a 6-1/2 digit resolution. High noise rejection is accomplished with an integrating analog to digital conversion technique that is synchronized to the a.c. power line. The standard resistor is used as a calibration check for the multi-meter. This resistor has an accuracy of .0005%, a one year stability of .0005% and a temperature coefficient of .0001% per degree centigrade.

The computer performs all the necessary actions to control the scanner, power supply and multi-meter to acquire the appropriate data. The gauge resistance is computed from the voltage and current reading for the active and compensating gauges. These resistances are then used with the calibration files to compute the coil stress as explained in the section "Determining Stresses from Measured Resistance".

The resistance measurement accuracy of this system is as follows:

- a. Reading resolution ± 0.7 milli-ohm.
- b. Short term: 24 hours, 3°C , ± 3.5 milli-ohm.
- c. Long term: 1 year, 6°C , ± 10.5 milli-ohm.

The implication of this system accuracy on the relative error of stress measurement is also discussed in the section on "Determining Stresses from Measured Resistance".

Calibrations

The transducers are calibrated by applying a known pressure through a coil stack to the surface of the beam and measuring the resistance of the gauge relative to its unloaded resistance at the same temperature.

The calibrations are performed at room temperature and at 4.2°K . Thus, when mounted in an assembled magnet the value of the pole face pressure can be obtained by accurately measuring the resistance of the gauge and determining the pole face pressure from the calibration curve. This method is valid for both room temperature and operating temperature measurements. A compensating strain gauge is provided in each assembly to measure the change in resistance of an unloaded gauge that is produced only from the magnetic field and temperature variation from the calibration temperature. In this way, the resistance measurement of the active gauge can be corrected for these effects to obtain a true pole face reading when the magnet is energized.

Calibrations are performed on gauge beams at ambient temperature, a pair at a time, in the fixture shown in Figure 7. A known total load is applied with a press or other type of loading machine to a stack of 10 layers of cable type superconductor. The stack of ten layers of cable is much more compressible than the beam and thus emulates the beam being loaded with hydrostatic pressure. However, this is not quite the case since the coil stack has some bending stiffness which increases with load level since the coil stack elastic modulus characteristically increases with pressure. The effect is that the calibrations curves are not quite linear with the increased coil modulus producing less change in microstrain output of the transducer beam with increasing load. This effect is shown in Figure 8 which is a typical calibration curve for one of the beam type transducers. The beams are fabricated to accurate

dimensions and must be flat to typically .0001 inch to achieve uniformly accurate and reproducible calibrations. Thus, the EDM process is used to fabricate the beams to ensure that these conditions are met. Typical calibration curves for different beams are therefore quite similar and the variation of measured microstrain vs. applied load is typically within 10 percent.

Determining Stresses from Measured Resistance

The coil stress is determined from the mechanically induced strain present in the gauge location of the beam bar at the time that the measurement is made. In order to do this, it is necessary to compensate for the apparent strain due to temperature changes and magnetic field effects, if present. This is done in the following manner:

Compensating Gauges

Each set of active gauges is provided with two (for redundancy) compensating gauges, of the same material as the active gauges, (see Fig. 3 for a detail of the compensating gauge) located in positions having the same magnetic field and temperature exposure as the corresponding active gauges, as was shown in Fig. 4.

Numerical Example

The following symbols are used in this discussion:

ϵ : mechanically induced strain in beam, in/in

R_{ma} : measured resistance of active gauge (nominally ~ 350 Ohms) with mechanical and apparent strain present

R_{mc} : measured resistance of compensating gauge with apparent strain

R_{a1} : measured resistance of active gauge in stress free condition at ambient temperature (i.e., $\sim 295^\circ\text{K}$)

R_{a2} : measured resistance of active gauge in stress free condition at a reference temperature near magnet operating temperature. It has been found convenient to make a simultaneous measurement of the unloaded active and compensating gauge in liquid helium at atmospheric pressure to obtain these reference measurements.

R_{c1} : compensating gauge measurement corresponding to R_{a1} .

R_{c2} : compensating gauge measurement corresponding to R_{a2} .

G_f : Gauge factor for particular type of strain gauge relating change in resistance to change in mechanical strain, typically $G_f \approx 2.0$.

s : compressive stress measured in magnet coil.

R_R : resistance ratio, change in measured resistance caused by mechanical strain divided by initial resistance of gauge.

$A_1, B_1, C_1, A_2, B_2, C_2$: least squares fit coefficients relating coil stress to R_R for (1), ambient temperature measurements, (2) operating temperature measurements. The coefficients are obtained from the quadratic least squares fit of the calibration data for each beam, i.e., $s = A_1 + B_1 \times R_R + C_1 \times (R_R)^2$.

Using the above definitions, we can obtain the coil stress from the measured resistances as follows:

For measurements near ambient temperature,

$$R_R = \frac{(R_{ma} - R_{a1}) - (R_{mc} - R_{c1})}{R_{a1}}$$

$$s = A_1 + B_1 \times R_R + C_1 \times R_R^2$$

If the measurements are made at operating temperature then the corresponding resistances and coefficients at $\sim 4.2^\circ\text{K}$ are used.

For the numerical example a typical measurement made during a magnet test is used. In this case the magnet temperature is $\sim 3.8^\circ\text{K}$ and a current of 7000 A is present which corresponds to a central field of ~ 7 Tesla.

The measured resistances in ohms for the active and two compensating gauges are:

$$R_{m2} = 350.3178$$

$$R_{c1} = 349.2203 \text{ and } 349.2299$$

The reference resistances for the active and two compensating gauges at 4.2°K are:

$$R_{c2} = 349.7893$$

$$R_{c2} = 348.9909 \text{ and } 348.9898$$

The beam calibration least squares fit calibration constants at 4.2°K are:

$$A_2 = 165.92$$

$$B_2 = 3.5218 \times 10^6$$

$$C_2 = 3.5626 \times 10^8$$

Thus, the total resistance change for the active gauge is .5285 ohms from its initial unstrained state at 4.2°K and the corresponding change in the average of the two compensating gauges was .2347 ohms due to the combined effect of the temperature change from 4.2°K to that of the operating temperature and the effect of the magnetic field. The resistance change of the active gauge caused by the mechanical strain only is therefore .2938 ohms. The mechanical strain resistance ratio, $R_R = .2938/349.7893$ or 84.0×10^{-5} . Substituting this value in the least square fit equation for coil stress gives a value of 3376 psi for the coil stress under these conditions. The relative error in the stress measurement can be estimated if it is assumed that the accuracy of the resistance measurement is $\pm .005$ ohms which is consistent with the previously mentioned accuracy of the resistance measurement system. The relative error in the stress measurement would be as follows:

Since the individual resistance measurements are uncorrelated, then the variance in resistance ratio is

$$\Delta R_R^2 = \sum_{i=1}^5 \left(\frac{\partial R_R}{\partial R_i} \Delta R_i \right)^2$$

where R_i are the five individual measurements to determine R_R and $\Delta R_i = \Delta R$ is the uncertainty in the measurements.

Performing the indicated partial differentiation,

$$\Delta R_R^2 = \left(\frac{\Delta R}{R_{c2}} \right)^2 \left(4 + \left(\frac{R_R}{R_{c2}} \right)^2 \right) = 4 \left(\frac{\Delta R}{R_{c2}} \right)^2 \text{ since } \left(\frac{R_R}{R_{c2}} \right)^2 \approx 0$$

Using $R_{c2} \approx 350$ and $\Delta R = .005$:

$$\Delta R_R^2 = (28 \times 10^{-6})^2$$

The variance in stress, from the equation for the least squares fit of the calibration data is

$$\Delta s^2 = \left[\left(\frac{\partial s}{\partial R_R} \right) \Delta R_R \right]^2 = \left[(B_2 + 2C_2 R_R) \Delta R_R \right]^2$$

with $B_2 = 3.5 \times 10^6$, $C_2 = 3.5 \times 10^8$, the accuracy of the calculated coil stress is ± 114 psi.

Measurements of Thermal Stress Change at Stress Change with Magnet Current

Thermal Stress Changes in SSC Magnets

Measurement of the thermal contraction in the azimuthal direction for SSC molded coils indicate that the thermal shrinkage from 300 K to 4.2 K is about the same as that of aluminum, i.e., $\sim .004$ in/in. The coils are assembled and compressed in stainless steel collars having a thermal contraction of $\sim .003$ in/in for the same temperature range. Thus, there would be a loss in compressive stress in the coils during cooldown. The thermal stress change also depends on complex mechanical factors affecting the assembly of the collared coils in the yoke such as the fit of the collared coil assembly in the yoke and the interaction of the thermal contraction of the helium containment shell as the magnet cools down. Such assembly dependent effects are not readily calculable and thus, the beam type transducers provide a method of measuring the polar stress of the coils as the magnet reaches operating temperature.

Several such measurements have been made on SSC model magnets and some examples are given in the following table:

Table 1: SSC Model Magnets. Thermal Stress Loss to Operating Temperature (Inner Coils, Polar Stress, psi).

Magnet Designation	Ambient Stress	Operating Temperature Stress	Delta Stress
DSS-006	8760	6660	2100
DSS-006R	7140	5100	2040
DSS-010	11850	4930	6920
DSS-011	9940	5530	4410
DSS-012	9550	4790	4760
DD-010	6060	3500	2560
DD-012	7010	5400	1610

Coil Polar Stress Change with Magnet Current

The SSC magnets operate at high current (~ 7000 A) and high field (~ 6.6 Tesla). The inner coils see the highest field and are thus subjected to large Lorentz forces which tend to move the conductors away from the poles. If the coils are not held in compression against the poles under these conditions the magnet could quench or suffer a loss of field quality. Thus, it is important to ascertain that the coils are always compressively stressed during magnet excitation in order to verify the adequacy of the design and determine the available operating margin. Again, the beam type transducers have been used for this purpose. An example of this variation in stress is given with some recent test results obtained from the 1.8 meter SSC model magnet DSS012. Figure 9 shows that the average zero current stress in the inner coils at the pole is about 4500 psi and drops about 2300 psi at 6500 amps. It is noted that the slope of the curves is not decreasing at the high current levels indicating that there is ample reserve coil stress to prevent unloading at the poles.

Measurement of Magnet End Forces

Measurements of magnet end forces are made with post type compression transducers approximately 1.38 inches long by .38 inches square with strain gauges mounted on opposite sides as shown in Figure 10. The aspect ratio of this bar is such that the gauges are mounted a sufficient distance away from the edges so that they see a uniform strain field free from edge effects. The two gauges on the opposite sides of the bar

compensate for bending effects and are required because there will usually be some bending moment on the bar when loaded in compression. When loaded, the bars produce a linear output of microstrain vs. applied load. The bars are calibrated at room temperature and at 4.2 K by applying compressive force in steps to about 7000 lbs. while measuring the microstrain output of each of the two strain gauges. The two microstrain readings are then averaged (for bending compensation) to obtain the calibration curve. A typical room temperature and 4.2 K calibration curve is shown in Figure 11. The measured average microstrain agrees well with the calculated value obtained from the compressive stress divided by the elastic modulus of the material of the bar. These bars are assembled in the end plate of the magnet such that the entire end force of the coils is supported on four of them as shown in Figure 13. These end force gauges are initially adjusted by screwing in the loading screw to produce a load typically of about 400 lbs. per bar or ~1600 lbs. on the magnet end while it is at ambient temperature. Each set of four end force gauges is supplied with two compensating gauges in order to correct the readings for the effect of temperature variation and magnetic field at the magnet operating conditions as was done with the beam type azimuthal gauges. These compensating gauges are mounted on the end plate near the active gauges so they are exposed to the same field and temperature. The measurement algorithm is therefore essentially the same as that used for the azimuthal gauges as explained in section on "Determining Stresses from Measured Resistance". When the magnet is cooled to operating temperature, the end force changes because of the difference in the thermal contraction of the coil assembly and the yoke and helium containment shell. This end force change is also related to the method of retaining the collared coil in the yoke; i.e. whether the coil is free to slide relative to the yoke laminations or clamped tightly in them and to the stiffness of the end plate. The ends of the SSC dipole magnets are also subjected to a large axial Lorentz force (~17,000 lbs.) at 6.6 Tesla, it is important known how much of this force is actually transmitted to the support plate at the end of the coil. Such measurements have also been made on SSC model magnets with these end force transducers. Some measurements of the end force change from cooldown to operating temperature and the effect of magnet current on the end force is shown in Figure 12 for some SSC model magnets. This indicates that the total magnet and force transmitted to the end plate increased by ~6000 lbs. at 7000 amps current.

FIGURE 1:

OLD STYLE SSC MAGNET COIL STRESS GAUGES

Figure 2 - Typical Variation of Total Resistance Change from Ambient to Low Temperature for Strain Gauges of the Same Lot Mounted on the Same Material.

Figure 3 - Beam Type Strain Gauge Transducer. Beam with Strain Gauge Mounted on It is Shown at Right with its Back-up Bar. The Beam with Assembled Back-up Bar is Shown in the Center. The Grooves in the Back-up Bar Allow Space for the Wires. A Compensating Gauge is Shown at the Left.

Figure 4 - Inner and Outer Coil Beam Transducers Mounted in Collar Pack with Compensating Gauges.

Figure 5 - Stress Variation along a .555 inch Span by .16 inch Thick Beam Loaded with 10 kpsi Coil Pressure.

4 WIRE RESISTANCE MEASUREMENT

Figure 6a

STRAIN GAGE MEASUREMENT SYSTEM

Figure 6b

FIGURE 7

BEAM STRAIN GAUGE TRANSDUCER CALIBRATION FIXTURE. TWO BEAMS ARE CALIBRATED AT THE SAME TIME USING FORCE TO APPLY LOADS UP TO 16,000 COIL STRESS. FOR LOW TEMPERATURE CALIBRATION, THIS FIXTURE IS LOADED IN A SPECIAL DEWAR FILLED WITH LIQUID HELIUM.

Figure 8 - Typical Calibration Curve for Beam Type Transducer Performed at Ambient Temperature and at 4.2K Using Fixture Illustrated in Figure 7.

Figure 9 - Variation of Polar Stress of Four Quadrants of a 1.8 m SSC Model Magnet under Test Measured with Beam Type Transducers to 6600 A.

Figure 12 - SSC 17 m Model Magnet End Force as a Function of Current as Measured with End Force Gauges from FNAL Magnet Test.

Figure 10 - End Force Transducer Shown with Loading Screw which Captures it and Loads it Against the End of the Magnet Coils.

Figure 13 - SSC Magnet Coil End Support Using Four Force Gauges to Load Coil Ends and Measure Forces.

Figure 11 - Typical End Force Gauge Calibrations Showing Difference between Slopes at Ambient Temperature and at 4.2K. Values Shown are Averaged from the Two Strain Gauges on Opposite Sides of Bar.

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