A DEVICE FOR PRECISION DIMENSIONAL MEASUREMENT OF SUPERCONDUCTING CABLE

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Abstract - A need for continuous sampling of the dimensions of superconducting cable has lead to the development of a machine for that purpose. This device measures average thickness, width, and keystone angle for a wide variety of cable sizes while under the mechanical loading anticipated in the final coil structure. Linear dimensions can be measured to ± .0001" and angle to ± .01°. Cable can be measured with and without insulation. Loading is variable up to 25 ksi. This device has applications in epoxy free coil winding where the cable dimensions must be well understood before coil winding in order to predict the size of the finished coil package. As a diagnostic device, it has application in the cable making process to help understand causes for subtle inconsistencies in cable dimensions. A possible quality control application exists. Current cable quality control requires destructive techniques with very small samplings, usually two samples for 5,000' of cable. We have evaluated device performance by repeated measurements of lengths of SSC cable.

INTRODUCTION

Cos θ type coils such as those intended for the SSC are made from multistrand keystoned superconducting "Rutherford type" cable. (The current SSC coil cross-section is shown in Figure 1.) In fabricating these magnets it is essential that the physical size of the cable be understood. In creating a coil geometry, the magnet designer specifies the conductor size necessary to fit the overall design parameters. These parameters include conductor placement and coil preload at operational temperature. Random variations in cable size will result in random errors in the magnetic field harmonics. Systematic variations in the cable size and thickness in particular perturb the preload, that is the azimuthal compressive force imposed on the coil via the collars to counter magnetic forces developed during operation. Variations in coil segments of a few mils can change required preload by several thousand psi and high preloads cause insulation degradation and clamp collar distortions. Coil fabrication techniques employing B-Stage Kapton or Kapton/B-Stage Fiberglass insulation with the coils molded to a given size allow some latitude in cable size tolerances due to the plastic nature of the insulation. There are, however, limits to the "adjustability" of this system as the major constituent of the coil composite is the cable. These limits reduce as the insulation is minimized to more efficiently use the superconductor.

*Operated by Universities Research Association, Inc., under contract with the U. S. Department of Energy.

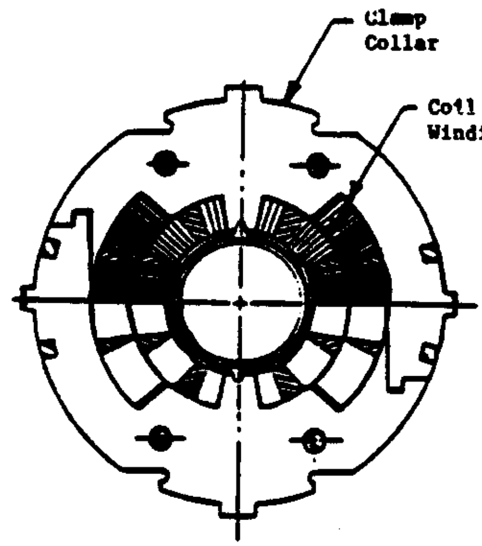

Figure 1. Cross-Section of a SSC Design D Collared Coil Assembly.

The coil preload can best be controlled by imposing tolerance limits on the cable. Current magnet manufacturing practices utilize measurements of the completed coil to assure that the coils in the magnet are of uniform size so as not to build in asymmetries in the assembled magnet. This is accomplished by remolding the coil after ascertaining its size following the first molding operation, thereby making all coils to a uniform size. Another technique is to carefully match upper and lower coil sets using the measurement data. In epoxy free coil designs in which coils are clamped directly by the collars and no molding is used direct coil measurement is not possible. Instead the cable size must be well enough understood to predict the coil size prior to winding. The coils can then be matched by selection of cable based on its measured size.

A cable measuring device was built at Fermilab as part of a program to develop epoxy free coils. This measurement technique clearly can be used to ensure consistent coil sizing and uniform wire placement in molded coils as well. The measuring machine described here could best be utilized in line with the cabling machine and could allow control of cable dimension to approximately a tenth of a mil (2.5 microns).

CABLE SIZE SPECIFICATION

Historically cable has been specified by the number of strands it will contain, the diameter of these strands, and helical pitch. Dimensions of width and thickness of the thin and thick edges (keystone angle) define the physical size of the cable. Tolerances are applied to these dimensions. Such a specification is incomplete in that consideration is not given to the fact that the cable is a composite having a variable spring rate. It is reasonable to expect the cable to be of varying size dependent on the loading conditions applied to it. The application of loads on cable used in cos θ magnets are compressive and normal to the plane defining the width. It is, therefore, appropriate and necessary for the cable specification to include a specified load when defining dimensions.

MEASUREMENT TECHNIQUES

Traditional cable quality control has evolved from micrometer measurements of the cable width and edge thicknesses to the present method of average thickness measurements obtained by stacking a number of cable samples with alternating keystone. While applying a specified load the stack height is measured with the average cable thickness assumed by dividing the stack height by the number of samples. This measurement has been standardized to have ten cable samples in the stack. The dimension of width is still made with a micrometer. The keystone is measured by applying a specified load to an individual sample through a pivotal platten. While these measurements are an improvement to previous techniques, they are destructive and applied only to a very small sample of the cable, typically obtained by cutting samples from the beginning of a cable reel and at best by samples taken from the beginning and end of the cable used for a coil leaving the actual cable used in the coil unsampled.

CONTINUOUS MEASUREMENT DEVICE

These shortcomings stimulated the development of a device which would enable continuous measurement of cable. The device developed at Fermilab was fabricated to specific criteria:

1. be capable of measuring moving cable allowing the measurements to be made in the cable insulating line,

2. be capable of measuring cable ranging in width of .280" to .450",

3. have variable load capacity ranging to 20,000 psi for a .435" wide cable allowing applied load to be selected to match the cable specification,

4. have the measured samples loaded across 6" of length so as not to measure the microstructure of the cable composite,

5. have a variable delay in measurement after applying the load to allow for creep to occur,

6. be capable of measuring over applied insulation without causing degradation to the insulation should measurements over insulation prove to be of value, and

7. be linked to a computer for data collection and processing.

The device is illustrated in Figure 2. The critical element of the machine is the measuring head (Figures 3 and 4). The head contains a rotating platten fitted to a cylindrical bearing surface. The load is transferred to the cable via hydraulic rams acting on the rotatable platten. Contact pressure with the cable causes the platten to rotate and conform to the angle of the cable. Extensions on each side of the platten amplify this motion. LVDT's (Linear Variable Differential Transformer) are used to measure the position of these extensions. The LVDT's are calibrated to solid steel gage blocks of known size and adjustable stops are used to keep the load centered on the cable. The LVDT's acting on the platten extensions are used to measure the keystone angle and average thickness relative to the gage block. Width dimensions are made using another LVDT which contacts a clamp bar. This LVDT is also calibrated to the gage block. The clamp bar uses two small pneumatic rams to force the cable between it and the cable centering stops. The load is sufficient to position the cable yet light enough to allow volumetric expansion of the cable when loaded. In operation the sequence of events is to first activate the pneumatic cylinder acting on the cable width clamp bar to properly position the cable under the measuring head. After a short time delay the hydraulic rams are activated. The moving clamped cable drags the measuring head along on linear motion ball bearings. After a predetermined time interval, the signal voltage of the LVDT's are read and the hydraulic and pneumatic rams are relaxed. A constant tension spring returns the head to its original position tripping a microswitch and restarting the process.

The hydraulic pressure is provided by an air over hydraulic booster. Air regulators are used to vary cable loading and are manually adjusted. An IBM PC is used to collect and store data. A program converts the voltage output of the LVDT's to cable dimensions through comparison to the gage blocks. Clamping pressure via a hydraulic pressure transducer and measurement position via a footage counter are recorded as well.

MEASUREMENTS

We have measured a length of SSC inner coil cable for the purpose of understanding the operation of the machine. These measurements were carried out over a 9-day period taking measurements at 6" intervals along 150' of cable with the loading set at 5,000 psi on the cable. The measurements were repeated six times on the same sample. These six runs averaged 2 runs per day. Each repeat measurement run sampled the cable at the same positions along the cable as the previous measurement run. To assure registration the cable measuring locations were marked and numbered on the cable. The measuring head was then manually positioned along the stationary

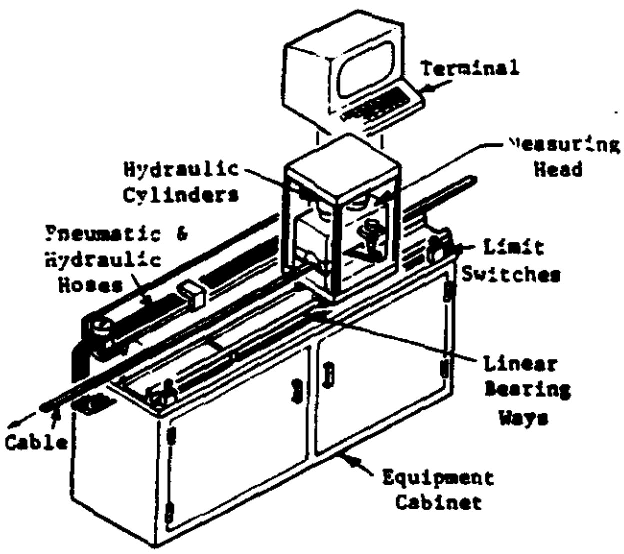

Figure 2. This figure illustrates the measuring machine installed in the cable insulation line.

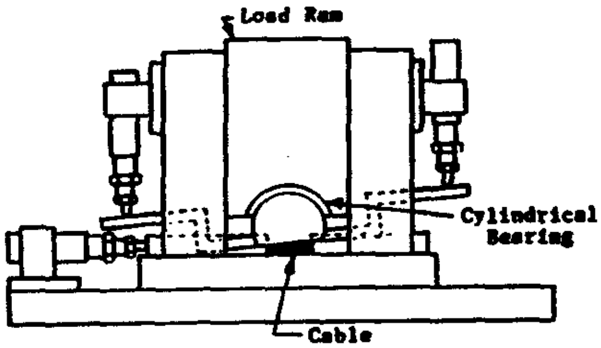

Figure 3. An end view of cable head showing cable during measurement.

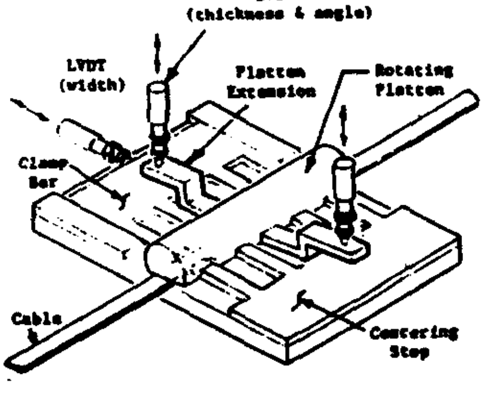

Figure 4. Isometric illustration of the measuring head with the load ram and guides removed for clarity.

cable with respect to these marks. This allowed eight measurements to be made before the cable had to be advanced. To discount any influence on the measurements which could arise from the measuring pattern the fifth and sixth runs were offset, that is, at the start of run #5, four measurements were made and the cable advanced returning to the normal pattern of eight measurements per cable advance for the remainder of the run. Prior to and following each run, steel calibration blocks were measured to detect any drift in the measurements. These blocks were used initially to calibrate the measurements of the LVDT's. Two blocks were used. The first is of a rectangular cross-section (used for calibration); the second block is made to a cross-section matching the specified dimensions of the cable being measured. The second block is used to cross-check the calibration.

RESULTS

The composite structure of the cable unlike the solid steel gage blocks becomes apparent in the cable measurements. After the first measurement run, subsequent measurements indicated a systematic reduction of all dimensions. The results of six measurement runs on one piece of cable are shown in Figures 5, 6, and 7 which plot the differences of each run from the average value for all six for each of the measurement points 100-125 (12.5 feet of cable). The figures clearly show yielding of the cable with each successive run.

To evaluate measuring machine performance without systematics due to this yielding or measuring head calibration shifts, each of the six runs was offset by the angle, width, and thickness averaged over the entire length of measured cable for that run. For each point on the cable, the deviation of the six measurements from the average for that point was calculated. The rms widths of these deviations are given in Table 1 and can be considered a good measure of the accuracy of the head when used to measure composite cable. Also shown in Table 1 are the rms deviations of successive measurements made on the solid gage blocks over a short period of time.

The data in Figures 5, 6, and 7 suggest that an operational definition should be applied when measuring cable closely correlated to the end use of the cable, that is, the magnet coils. Such a definition could define the application of the load to the sample being measured. For example, the cable could be first loaded as anticipated in the coil molding process, relaxed, and then loaded again to the expected collar load with measurements recorded at that time. This issue is secondary to the primary use of the machine which is to measure cable. The results in Table 1 clearly indicate the capability of the machine to do that quite respectably.

Table 1

RMS Deviations from Average Values		
	Calibration Block	Cable (Systematics Removed)
Angle	± .001°	± .01°
Width	± .01 mils	± .04 mils
Average Thickness	± .02 mils	± .02 mils

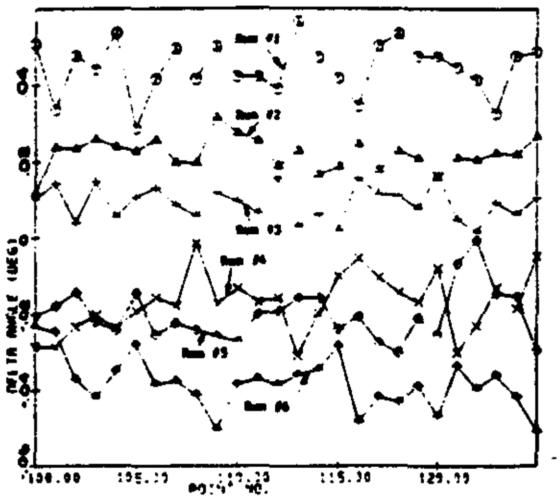

Figure 5. Cable Keystone Angle.
Plotted is the difference between each of six measurement runs on the same cable and the average for all six runs. The 25 points shown (100.00-125.00) represent 12.5' of cable.

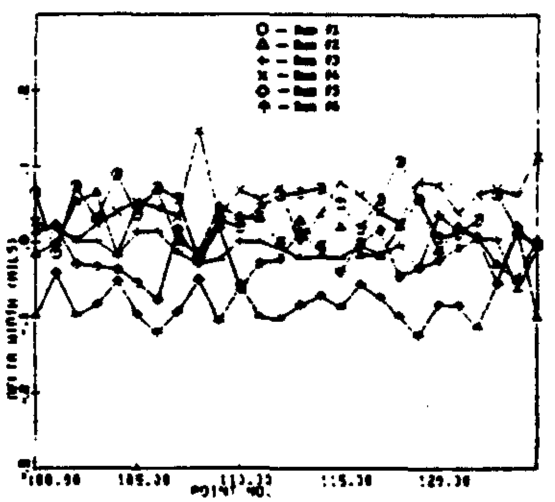

Figure 6. Cable Width.
Plotted is the difference between each of six measurement runs on the same cable and the average for all six runs. The 25 points shown (100.00-125.00) represent 12.5' of cable.

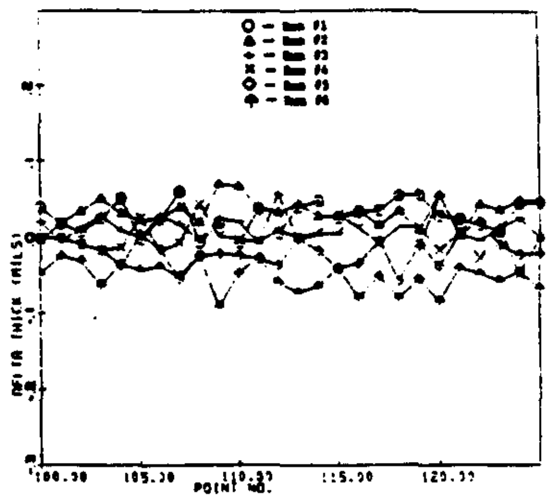

Figure 7. Cable Average Thickness
Plotted is the difference between each of six measurement runs on the same cable and the average for all six runs. The 25 points shown (100.00-125.00) represent 12.5' of cable.

APPLICATION

Application of this device can be considered for Q.C. of cable by the user. It has similar, if not superior value, to the cable manufacturer. In order to produce cable consistently to a high degree of accuracy, the cable size should be monitored on a continual basis. Subtle changes in cable dimensions could be observed and adjustments made immediately. As a diagnostic tool, it has potential for helping sort out causes of cable variations and help focus in on areas needing improvement.

ACKNOWLEDGEMENTS

The authors wish to express their thanks to B. Howell, R. Rioux, and S. Gould, all from Fermilab's Technical Support Section, for the assembly of the apparatus and for the effort in taking these measurements.