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Design and Use of Capacitive Force Transducers for Superconducting Magnet Models for the LHC

N.Siegel, D.Tommasini, I.Vanenkov

Abstract

Capacitive force transducers have been developed and used for monitoring the coil pre-stress during assembly and excitation of several dipole models for LHC. Typically these gauges are strips several tenths of millimeter thick that can be made according to a large variety of geometries. Inserted between two surfaces, they allow to measure the distribution of contact pressures up to 200 MPa from ambient temperature to superfluid helium also in presence of a static magnetic field. The sequence and quality of the manufacturing steps are determining factors in the performance of this kind of gauges. The paper describes the basic principles, possible configuration geometries, fabrication and calibration procedures. Finally the applications of capacitive gauges in the framework of the R&D programme of superconducting short dipole models for LHC are reviewed and discussed.

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Design and use of capacitive force transducers for superconducting magnet models for the LHC.

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Abstract - **Capacitive force transducers have been developed and used for monitoring the coil pre-stress during assembly and excitation of several dipole models for LHC. Typically these gauges are strips several tenths of millimeter thick that can be made according to a large variety of geometries. Inserted between two surfaces, they allow to measure the distribution of contact pressures up to 200 MPa from ambient temperature to superfluid helium also in presence of a static magnetic field. The sequence and quality of the manufacturing steps are determining factors in the performance of this kind of gauges. The paper describes the basic principles, possible configuration geometries, fabrication and calibration procedures. Finally the applications of capacitive gauges in the framework of the R&D programme of superconducting short dipole models for LHC are reviewed and discussed.**

I. INTRODUCTION

Pressure transducers are needed in a variety of cases in the framework of the R&D program for the LHC magnets. The superconducting cable of these magnets is pushed to its limits to provide the highest magnetic field in the smallest space. This requires a strong clamping structure to constrain the conductor in a stable position. Extensive measurements of the mechanical status of the coils and of the surrounding structure during magnet assembly and during the excitation in superfluid helium are currently carried out at CERN mainly by using methods based on strain gauges [1]. This kind of measurements requires a long and accurate phase of design and preparation for the adaptation of the structure to the devices and for the data acquisition and analysis. Furthermore gauge sizes and limitations in the geometrical configurations do not allow carrying out special tests like monitoring pressure gradients over distances of few millimeters (like a cable width), mid-plane stresses and other.

In these cases, and in general when a relatively non-invasive measurement of pressures between surfaces is required, capacitive gauges offer a simple and reliable solution.

II THE GAUGES

A. Basic principles

The idea of using the capacitor as a load cell is not new and is widely described in literature [2].

The simplest electrostatic transducer has two parallel plane electrodes of area **S** with a dielectric material of thickness δ and electric permittivity ε in between. The capacitance **C,** without considering fringe field effects, is given by:

$$C=\varepsilon S/\delta$$

If the modulus of elasticity of the dielectric material is much smaller than the one of the electrodes, when an external pressure is applied on the capacitor the capacitance will change due to the variation of δ according to the relationship:

$$C=\varepsilon S/(\delta(1-\sigma/E))$$

where σ is the applied stress and **E** is the modulus of elasticity of the dielectric material. The linearity of this transducer mostly depends on the mechanical properties of the dielectric material and on its boundary conditions. To increase the yield limit and to limit the Poisson's deformation of the dielectric, the design of the transducer must be made such that the dielectric material is put under hydrostatic stress condition. This is achieved by gluing the dielectric material film between rigid electrodes in order that the dielectric does not flow under pressure. In this case the electrodes play a double role: first as a conductor for electrical purposes and second as a mechanical shell to support the dielectric material. To match the above conditions, the good choice of the bond type and dielectric material and a rigorous assembly procedure play an important role.

B. Fabrication

The gauge consist of a "sandwich" of stainless steel foils interleaved with polyimide films glued together (Fig.1).

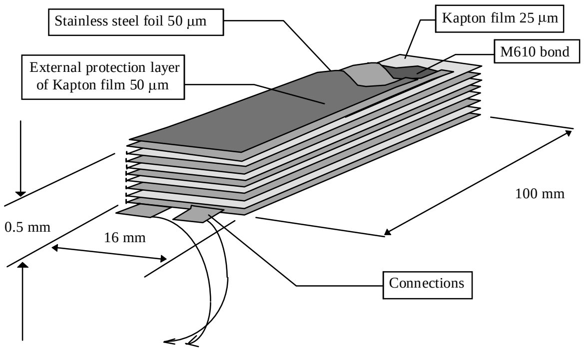

Figure 1. Typical layout of a capacitive force transducer.

The sensitivity of the gauge is directly dependent of the modulus of elasticity and of the electrical permittivity of the dielectric. For conditions prevailing in superconducting magnet applications (high pressure cycling in a wide range of temperatures), polyimide tapes are well suited.

As the transducer will work inside magnets no ferromagnetic material should be used for the electrodes. The electrode material should be strong enough to stay in the elastic region under the maximum load pressure applied to the transducer. To match these conditions non-magnetic 316LN stainless steel foils have been chosen. The foils, typically between 25μm and 50μm thick, are pre-plastified under a pressure of 200MPa.

The bonding has to prevent the border of the polyimide film from moving relative to the electrode under the high pressure load and must remain elastic at liquid helium temperature. The high-performance epoxy resin M610, developed by Micro-Measurements® for strain gauges applications, was chosen as glue. This glue has a good elongation factor, a long cycling fatigue limit and can operate from liquid helium to 175°C.

The fabrication technique consists of two important steps: the preparation of the gauge components and the gluing procedure. In order to achieve a good performance the dimensions of the electrodes in the "sandwich" must be precise and the strips well aligned.

After assembly the stack is cured in a mould under a constant pressure at 140°C during 2 hours. The width of the dielectric tape is taken intentionally much wider than the final size of the gauge for easy manipulations during the "sandwich" assembly and fixation in the curing mould. The extra-part of dielectric is cut off after the gauge is cured.

From the experience with strain gauges the same technique was used to train the gauge for a better performance especially at cold. After the fabrication, the gauge needs to be pre-cycled at a pressure 20% higher than the operating one with a certain number of thermal-cycles in liquid nitrogen afterwards. After this training the internal stresses in the "sandwich" are re-distributed and the creep and non-linearity of the gauge are minimized.

C. *Calibration*

A hydraulic press up to 50 t was used to calibrate the capacitive force transducers. For special configurations like three-strip gauges, which will be described below, a special set up which avoids asymmetries in the load needs to be used. Typical calibration are shown in Fig. 2. The calibration curves have a small non-linearity at the very beginning of the load and some hysteresis during load-releasing cycles due to a relatively slower relaxation of the size of the polyimide tape on release. These effects are in general very small, and even with a linear approximation of the calibration curve the deviation from linearity is not more than ±5% over the range of pressures up to 200 MPa.

The stray capacitance of the wires and the connections has a significant value and must be taken into account during the measurements. In case of connection with four coaxial wires per gauge the change of temperature of the cable down to superfluid helium do not change the reading from the gauge. In order to eliminate the effect of gauge surrounding materials to the stray capacitance an odd number of electrodes must be used [2].

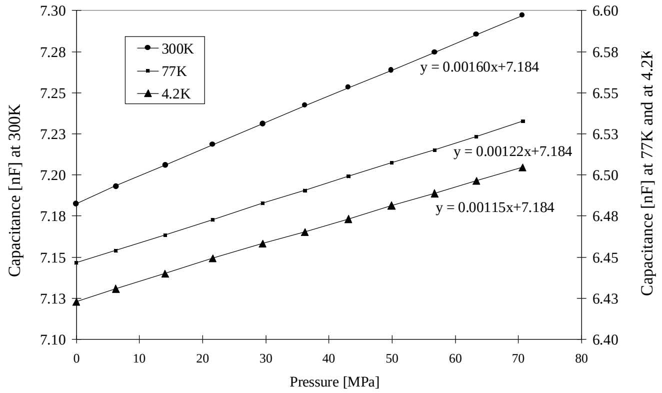

Figure 2. Typical calibration curve of a capacitive gauge.

In Figure 3 the "zero" of the gauge at 4K is shifted by about 800 pF compared to the zero at 300K: this is the Apparent Capacitance value (AC). This AC is similar to the Apparent Strain from strain gauge's technique and comes mainly from two factors: change in dimensions due to thermal contraction effects and due to the change of permittivity of the polyimide at cold. The sensitivity of the transducer in the example is ~ 1.60 pF/MPa at ambient temperature and ~ 1.12 pF/MPa at 4K. The 30% smaller sensitivity at cold is mainly due to the increasing of the Young's Modulus of the dielectric tape at cold. After calibration of a series of transducers made with different dimensions and number of layers, it was noticed that this reduction of ~30% is in general well reproducible.

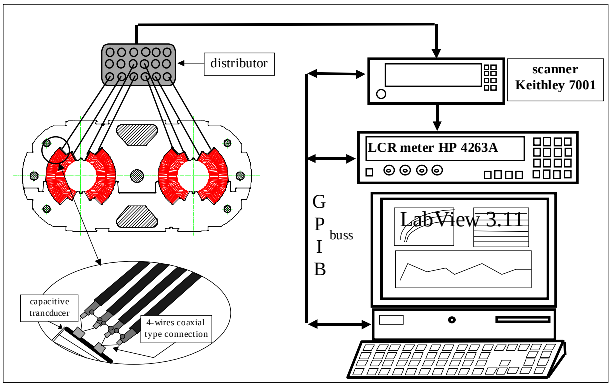

Figure 3. Schematic layout of the data acquisition system.

III THE DATA ACQUISITION SYSTEM

In order to be able to acquire signals from several capacitive probes at the same time, a multichannel data acquisition system based on a LCR meter (Hewlett Packard 4264A), and an analogue multiplexer (Keithley 7001) driven by a PC was developed for a series of magnet tests at CERN. A schematic structure of the system is shown on Figure 3. Through the GPIB interface a program written in LabView® activates in scan mode one channel and acquires data into the PC. After each scan the data is transformed into pressure in a table format according to the individual calibrations of the various transducers connected to the system.

IV APPLICATIONS

Capacitive gauges are being used at CERN in a variety of shapes depending on specific needs. A few applications among the many already experimented will be described below.

A. Collaring test of a LHC twin aperture dipole section.

To monitor the coil stress during collaring and the loss of coil pre-stress at cold of a LHC double aperture dipole section, eight transducers were used as a portion of the standard pole shims on the upper part of a 100mm long aluminium collar pack. The transducers, 0.5mm thick and of the same length as the collar pack, are made in 6 dielectric layers. These transducers were preliminary calibrated at both ambient and liquid nitrogen temperatures up to 200 MPa and cycled several times for measuring the AC values. After the second collaring, the coil assembly was cycled two times to 77K. The layout of the gauge position is the one shown in Figure 4; the measured coil stress is plotted in Figure 4.

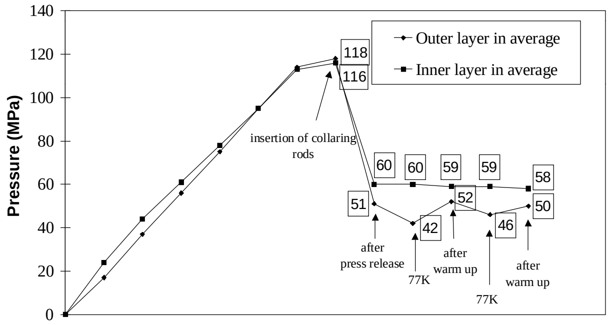

Figure 4. Collaring and cool-down of a LHC dipole section.

The test results show that the inner layer pre-stress from ambient temperature to liquid nitrogen does not change in an appreciable way. For the outer layer the loss of pre-stress from ambient temperature to liquid nitrogen is of about 9MPa after the first cycle and only 4MPa for the last cycle. A similar behaviour has been found also in other cases and suggests an adjustement of the coil-collar matching during the thermal cycle.

B. Single aperture collaring test with aluminium collars.

A cross-check with the well established instrumentation based on strain gauges has been carried out on a single aperture dipole section 100mm long, collared with aluminium collars. The capacitive gauges were placed on each pole of both inner and outer layers. The layout of gauge positioning is shown in Figure 5.

The measurements of the stress in the coils obtained from these two different methods were made at the same time and gave quite similar results. After collaring, the coil-collar assembly was cycled two times to 77K. Results of these measurements are given as averages for both the inner and outer coils in Figure 6.

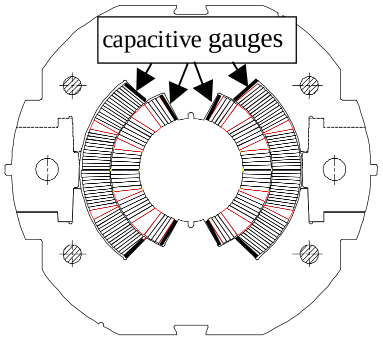

Figure 5. Layout of capacitive gauges positions (8 gauges).

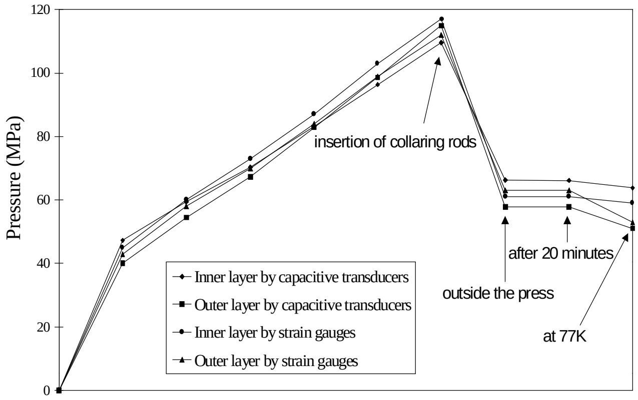

Figure 6. Coil stress measured by capacitive and strain gauges.

At ambient temperature between the two systems there is a non linear shift. In particular up to about 60 MPa the difference is within ±2MPa, at higher stress values the difference increases especially for the inner layer up to 7MPa at 110MPa. This effect, which is in any case small and within the ±5% which is commonly assumed for this kind of instrumentation, could be probably explained by the different information the two devices give and by the different calibration approaches. The capacitive gauges measure the total force acting on each coil layer, integrating local pressures. Furthermore they are calibrated over the full range of applied loads, from 0 to 150MPa. The strain gauges, which are stuck onto the collars, give a signal which is proportional to the local strain on the collars where the gauge is placed. In particular, especially for the inner layer, due to the space available, the gauges are placed not corresponding to the middle of each coil layer, but slightly displaced outwards.

C. Assembly and test in superfluid helium of a short dipole model made with stainless steel collars.

One of the short model dipoles, MBSMS3, has been re-collared in a new version with non-magnetic steel collars [3]. The azimuthal coil stress has been monitored during assembly and during the tests at cold with 90mm long capacitive gauges placed between the coils and the collar noses. One of these gauges on the inner layer was made in three different parts to monitor the coil pressure along the cable width.

Due to the favourable stiffness ratio between collars and coils, the spring-back after collaring is higher than with aluminium collars (about 60% instead of 50%). During cool-down however the coil pre-stress decreases by more than 50% due to the thermal contraction of stainless steel which is lower than that of the coils.

The evolution of the pre-stress at cold during magnet excitation is of particular interest especially for the inner layer. The plot in Figure 8 shows the non uniform radial distribution of the Lorentz forces on the inner layer coil. Before excitation the internal part of the cable is submitted to the highest pre-stress, at the highest fields all the cable surface is close to unloading.

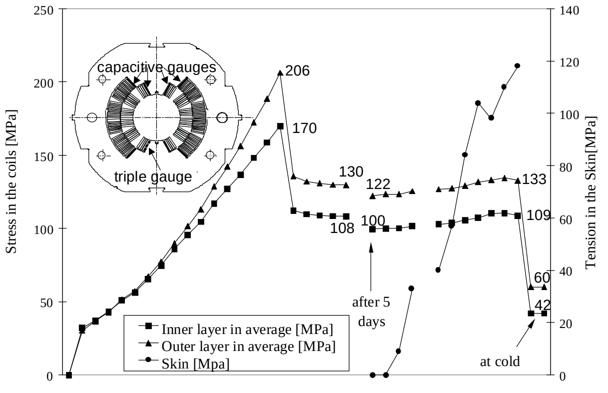

Figure 7. Assembly chart of MBSMS3.

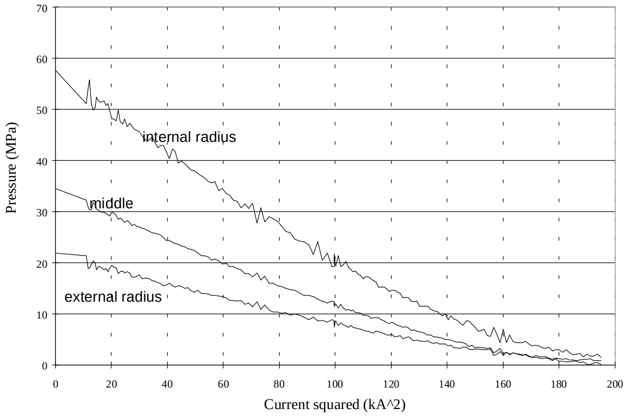

Figure 8. MBSMS3 : change of coil pressure as a function of current, measured by triple capacitive gauges.

D. Median plane pre-stress measurement in the coil ends of dipole model magnets.

The coil ends of the short dipole models of CERN are impregnated with an epoxy resin and shimmed in the median plane to achieve after collaring a pre-stress which compensates the azimuthal component of the Lorenz force. Due to the rather complex structure of the coil ends it is difficult to obtain from computations the spring-back after collaring and the pre-stress losses at cold. For this purpose special “matrix type” capacitive force transducers were developed and installed in the median plane of the coil ends of a dipole model. After the standard collaring, the whole assembly was cooled down to liquid nitrogen: the peak compression under the press, the spring-back and the loss at cold have been measured. The layout of the “matrix” capacitive gauge and the results of this test are shown on Figures 9 and 10.

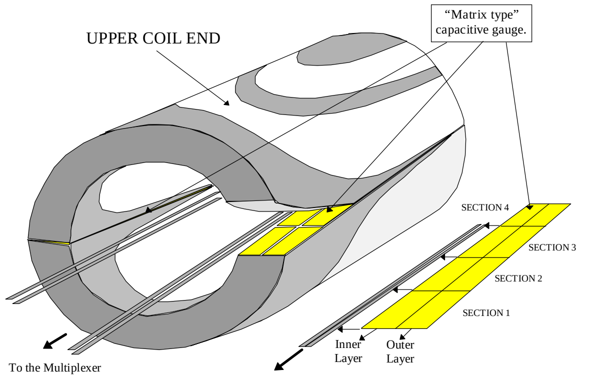

Figure 9. Measuring coil pre-stress in the heads : layout of gauges.

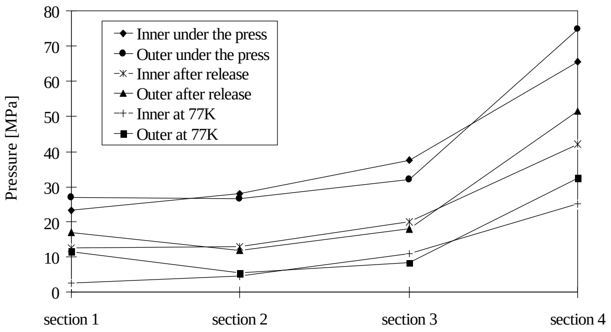

Figure 10. Evolution of coil pre-stress during collaring and cool-down.

V CONCLUSIONS

The use of capacitive gauges for monitoring pressures up to 200MPa from ambient temperature to superfluid helium is continuously increasing at CERN. These gauges can be precisely calibrated separately from the structure to be measured and the data acquisition system is relatively simple and economic when compared to that needed for other methods. It is planned to use capacitive gauges of the type described in this paper for the development of different types of the LHC magnets, like the main quadrupoles, the low-β quadrupoles and the corrector magnets.

ACKNOWLEDGEMENTS

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