Calibration of a Probe for Strain Sensitivity Studies of Critical Current Density in Superconductors Wires

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Abstract

This report describes the activity performed during the summer internship at Fermilab, in the period August-September 2012, as a Fermilab Guest supported by an ASI-ISSNAF grant.

The research was carried on at Fermilab Technical division, in the Superconducting Materials Department, within the Strand and Cable R&D group led by Emanuela Barzi.

I worked with Daniele Turrioni to develop the electronics aspects of the project and with the technicians of the lab to build up the experimental setup.

The main topic of my work was the calibration of a probe designed to develop strain sensitivity studies of critical current density in wires of superconducting material, such as Nb_3Sn.

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1 Introduction

The technology of superconducting magnets requires accurate measurements of critical current density and in particular of strain sensitivity. It is important to understand how the the different properties of superconductors change due to an induced strain.

The use of brittle superconductors makes this demand compulsory.

The stress on superconductors could arise from several sources:

- fabrication
- thermal contraction
- magnetic force

The scope of our work is to properly calibrate a probe to perform such analysis.

2 The probe

The measurement are performed using a bending spring technique put in practice in the probe [1].

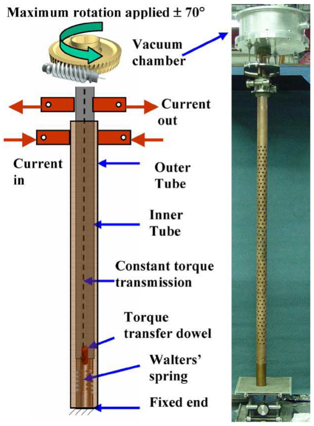


Figure 1: The probe

The device, fig.1, is made of two concentric OFHC copper tubes which act as current and torque carriers.

The top of the spring is attached to the inner tube and can rotate, while the bottom is fixed to the outer tube.

Torque is generated through a manual worm gear and transferred to the sample that is soldered on the spring.

This configuration makes possible to transfer both tensile and compressive state.

2.1 Walter Spring

The spring is the core part of the probe.

It is made of Ti-6Al-4V alloy which guarantee high elasticity limit at operating condition of liquid Helium at 4.2 K but has poor solderability properties.

The designed baseline is of 4 turns.

The geometry is a result of an optimization made in order to:

- minimize the ratio of the strain between the inner and outer surface of the spring
- reduce the strain gradient along the wire to be measured

It has a T-shaped section with a groove to place the specimen. This kind of installation makes possible to have compressive state but causes an additional strain due differential contraction.

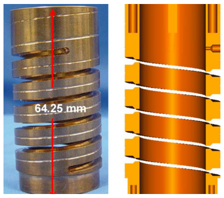


Figure 2: Walter Spring

3 Objectives

We will use strain gauges to capture the strain ϵ.

We want to verify the relation between the imposed angular displacement and the strain on the spring. The aim is to verify the relation computed analytically and through finite element analysis.

We want to check:

- linearity
- hysteresis
- reproducibility
- different prestrains with different installation
- strain uniformity along the spring

4 Model

We developed both an analytical model and a finite element model [1] of the spring.

4.1 Analytical model

4.1.1 Strain

The spring is treated as a curved beam, each turn represents a curved section.

We can compute the circumferential strain:

$$\epsilon_{\theta\theta} = K(1 - \frac{r_n}{r}) \tag{1}$$

where K is a factor that depends on the applied angular displacement, the number of turns of the spring and the pitch angle, r_n is the radial position of the neutral axis.

4.1.2 Geometry

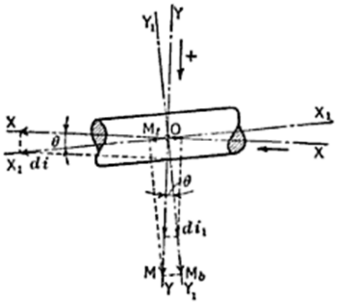
We can exploit this representation of the spring to compute the expected geometrical variation.

This is an important feedback we could have to check the validity of the model at room temperature, where we have a direct access the device and is possible to measure the mean diameter, angular distortion of turns and total vertical length of the spring.

One of the geometrical quantities we want to measure is the angular distortion of the turns ω which is the rotation about the axis OX as in Fig3. The figure represents an element of the spring, the Y axis represents the vertical axis of the spring.

The deformation of the turns is significant cause it's one of the sources of the differences between the analytical and FEA model. In fact just the latter considers it in the model.

Figure 3: Spring element model



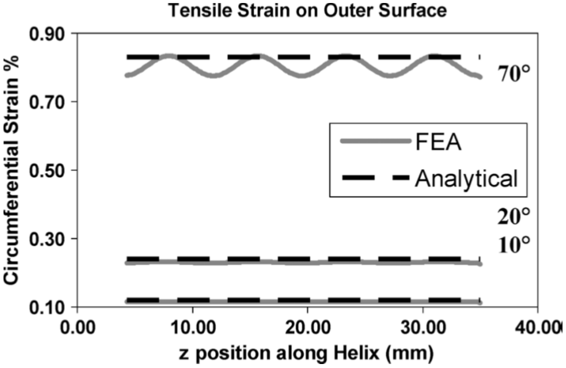
4.2 Finite element model

A finite element model was developed to verify the analytical predictions.

It is useful because it helps catching the shape distortion influence that are not taken into account with the previous model.

In fact the FEM shows a sinusoidal variation of the strain along the helical path of the spring.

Figure 4: analytical and FEA analysis [1]



5 Strain Gauge

There are several aspects that we need to take into account dealing with strain gauges.

Considering the type of measurement, operating temperature, test duration accuracy and cyclic load, we use the model WK-05-062AP-350 option L.

Specs:

- W : carrier matrix, Integral printed circuit terminal, polyimide encapsulation
- K : foil alloy, Nickel-chromium alloy
- 05 : STC number (Ti alloy) / 09 for BeCu
- 062 : active gauge length in Mils (0.001 in [0.0254 mm])
- AP : Grid and Tab Geometry
- 350 ± 0.3: Resistance in Ohm
- L : pre-attached leads
- Strain range: ±1.5%
- Fatigue life : $\pm 2200 \mu m$ Strain level ; 10^6 Number of Cycles

WK-Series gauges have the widest temperature range and most extensive environmental capability of any general purpose strain gauge of the self-temperature-compensated type. They present a reinforced epoxy-phenolic backing useful for handling, bonding and electrical insulation.

5.1 Installation

The strain gauge installation is a crucial part of the test procedure cause the binder becomes part of the load transfer system.

It affects greatly the quality of the measurements and becomes the primary factor of failure.

We want to maximize the information that we can achieve from the test using the smallest number of strain gauges possible since the room for them and their cables in the cup that embody the spring is very little.

The difficulties arise from the geometry on which the gauges have to be placed. Strain gauges are supposed to lay on plate surfaces while we have to cope with a curved one.

Since the FEA analysis shows a sinusoidal variation of strain particularly at high angular displacement, we decide to put 3 SG 180° apart trying to catch this behavior.

We place 3 gauges on the 2 central turns oriented through the longitudinal direction to catch the helical strain.

We also have a fourth gauge which is not glued as the others acting as dummy gauge.

The function of the dummy gauge is to compensate the effect of temperature on the gauge.

5.1.1 Wheatstone bridge

The different strain gauges belong to different Wheatstone bridge used in the quarter bridge configuration cause we need different measurements output.

The dummy is included in an half bridge with one gauge. We could appreciate the differences between compensated devices and not.

6 Room Temperature test

The first phase is needed to figure out which is the best configuration and to check that all the components of the measuring chain work properly. We can also have important information since we have a physical access to the spring and test the probe both horizontally and vertically to check the weight of the probe influence on the prestrain.

6.1 Operation

We apply the angular displacement from 0° to $+70°$ (inducing a tensile stress) even though the design of the probe would allow more angular displacement. We want to be sure to remain in the elastic field in order to check the *reproducibility* of the measure.

We also perform a test in compression: from 0° to $-70°$.

The limit varies according to which spring material is in use. Ti alloy has an elastic range wider than BeCu, the other material that would be testes in future configuration.

7 Results

We show the results obtained at room temperature with the probe lied horizontal.

Strain gage labeled 3 is the one placed in between the other two. Considering the 2 central turn of the spring, SG2 is at 0 degrees, SG1 at 180 and SG3 at 360 of course following the helical path.

SG3 is the one connected with the dummy.

Figure 5: Tensile Strain State

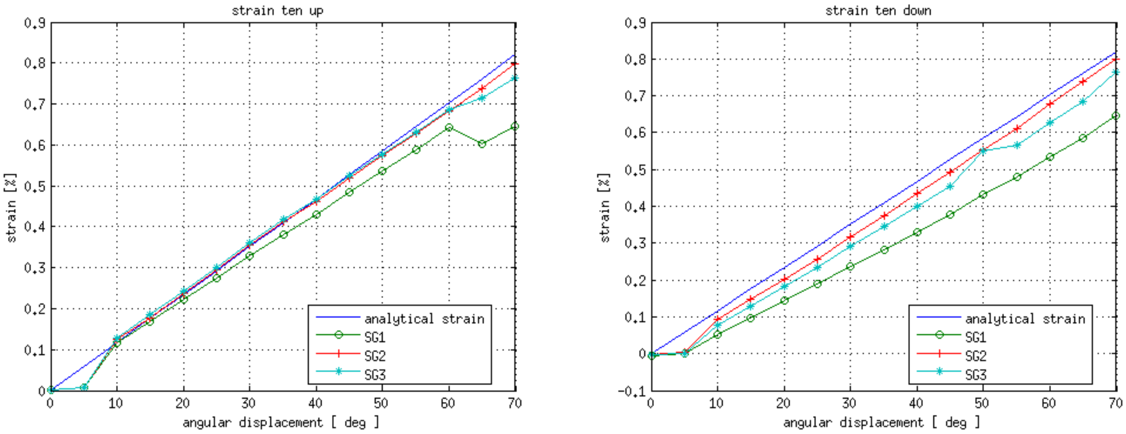
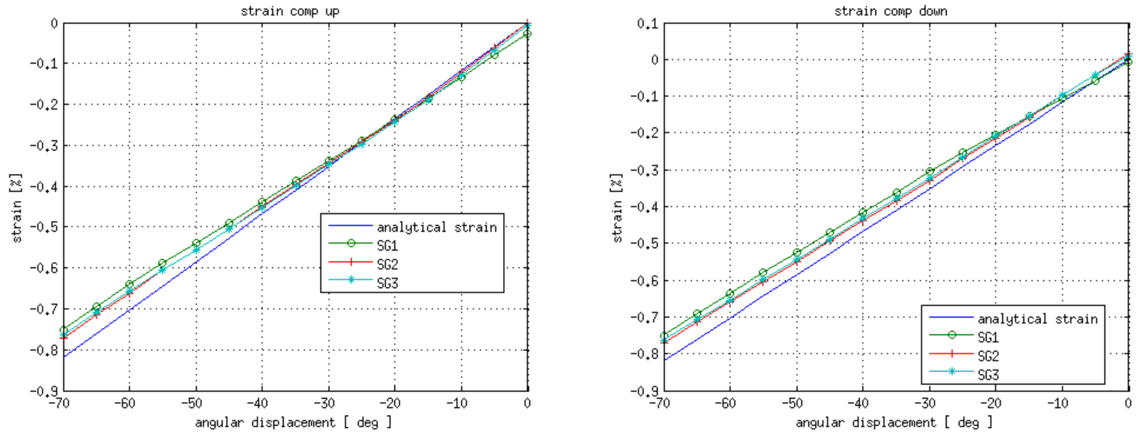
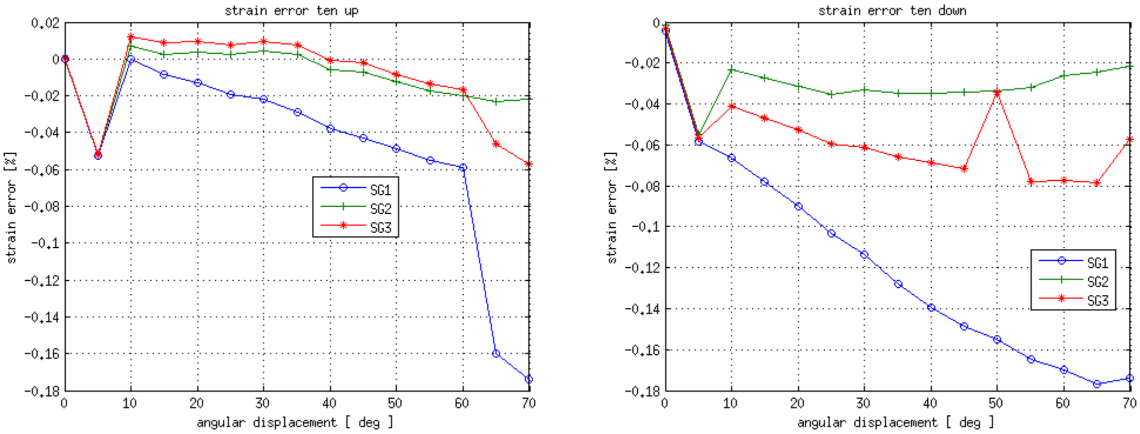


Figure 6: Compressive Strain State



We already expected calibration factor lower than analytical and FEA result. This is due to connectors and shafts. Moreover analytical expected strain is larger than FEA cause doesn't take into account radial compression.

Figure 7: Tensile Error

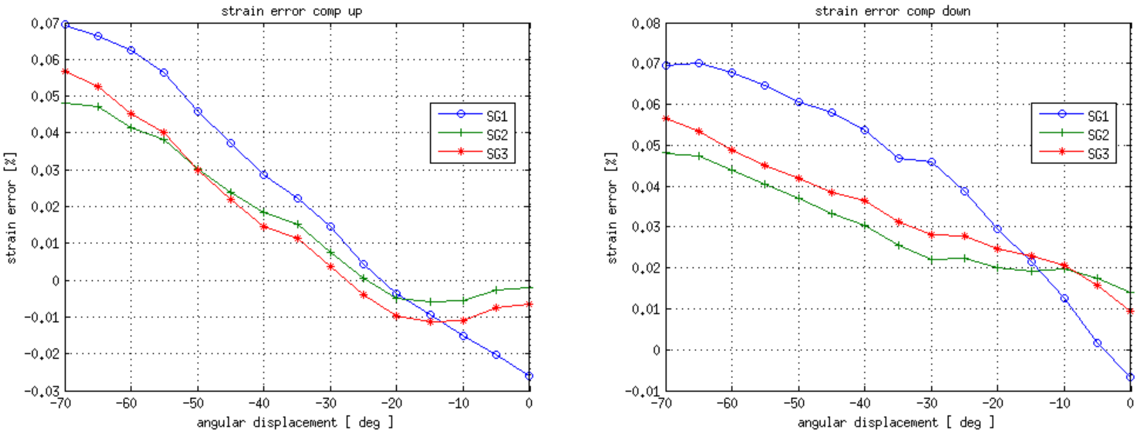


We see that the error between the strain gauges output and the analytical value is within the 7.5% taking into account the tensile state we called coup's, which means that the load is applied from 0 to +70 degrees.

The case we called downtown, when we release the load coming back to zero, shows higher level of strain. We expect some hysteresis cause we are not ideally loading the spring quasi-statically and we are also not so far from yielding point.

Anyway repeating the measurement, with the same setup, we have not experienced any zero offset.

Figure 8: Compressive Error



Data belonging to compressive state show that in this case the error is lower. This is probably due to installation problem.

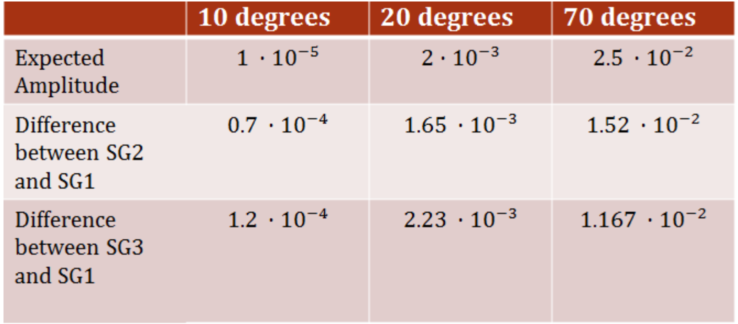
7.1 Strain uniformity

The goal of checking strain uniformity along the spring drives the particular set up of the gages.

We can now show that experimentally we find out about the same amplitude which was expected from finite element analysis.

We report the data obtained at three different loading steps. We see that the amplitude increases with larger angular displacement and this behavior is confirmed by strain gauges output.

Figure 9: Strain Uniformity



	10 degrees	20 degrees	70 degrees
Expected Amplitude	$1 \cdot 10^{-5}$	$2 \cdot 10^{-3}$	$2.5 \cdot 10^{-2}$
Difference between SG2 and SG1	$0.7 \cdot 10^{-4}$	$1.65 \cdot 10^{-3}$	$1.52 \cdot 10^{-2}$
Difference between SG3 and SG1	$1.2 \cdot 10^{-4}$	$2.23 \cdot 10^{-3}$	$1.167 \cdot 10^{-2}$

8 Source of errors

Possible source of errors are due to:

- hysteresis
- zero-offset due to impedance difference
- temperature effect on sensitivity
- zero shift with temperature
- EMI: errors due to amplification

An estimation of these errors

9 Cryogenic test at 4.2K

In the second phase we need to check the results of the base configuration in this new operating condition.

The goals are:

- Check differential thermal expansion
- Measure strain induced by thermal load during cooling
- Check gauge factor difference
- Spring material difference
- Repeat check of previous step
- Calibration curve for operative use

If possible we should reuse the same strain gauge setup for previous test to avoid installation differences.

9.1 Thermal contraction

The thermal contraction of the Ti alloy, when the temperature changes from 295 K to 4 K, is 0.17%. While the thermal contraction of the Nb_3Sn wire, of which the specimen to be soldered on the spring is made, is 0.28% so the wire constricts against the spring as it is cooled down toward the measurement temperature.

At this net 0.11% of tensile state we have to subtract the magnetic strain.

If we consider a current of 1000 A at 4.2 K during 12 T measurement the Lorentz force causes a differential contraction of 0.06% and so the Nb_3Sn is subjected to to a total tensile strain of +0.05 %.

9.2 Temperature compensation

We install an additional strain gauge in order to measure the induced strain on the transducer due to the thermal load.

We can place it on the upper part of the spring but is not an important issue since we actually don't glue it. It just must experience the same temperature of the spring.

Choosing appropriate α_g and α_p thermal expansion coefficient of the sample and the grid, we can reduce the interference of temperature

$$\Delta R/R = \Delta T(\alpha_p + k(\alpha_m - \alpha_g)) \tag{2}$$

Since we are using quarter bridge we need to compensate also the effect of temperature on cables

9.3 Operation

We cool down the probe through 4.2 K checking the induced strain during the procedure.

Then we repeat the same operation done at room temperature. If it will be possible we should reuse the same SG to avoid noises due to installation differences.

10 Conclusion

From the results shown at room temperature we can achieve enough data to build a calibration curve that is well predicted by our analytical and finite element analysis.

These data must be checked in the cryostat tests with further measurement to actually check the differences form the operative environment.

References

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