CAPACITIVE STRESS GAUGES IN MODEL DIPOLE MAGNETS

A Senior Scholars Thesis

by

Robert Blake Ragland

Submitted to the Office of Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

April 2009

Major: Physics

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Associate Dean for Undergraduate Research:	Robert C. Webb

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ABSTRACT

Capacitive Stress Gauges in Model Dipole Magnets.
(April 2009)

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Department of Physics

Capacitive transducers are used to measure mechanical stress in the windings of superconducting magnets. The transducer consists of a bonded laminate of alternating thin foils of stainless steel and high-strength polymer (polyimide). The thin, flat package is ideal for measuring the accumulation of Lorentz stress that develops in the windings when current is passed through the coil to generate magnetic field.

All groups who have used these transducers have experienced problems with failure of the gauges during operation. The Texas A&M group is endeavoring to determine the causes of the failures and remedy them so that we can continue to use the transducers in our next model dipole.

During the construction of the previous model dipole, called TAMU II, there were transducer failures at very high ramp rates. From the raw measurements many insightful observations can be made including stress magnitudes, distributions, and magnetic field variance as a function of those stresses. My goal is to improve upon current methods of transducer fabrication to yield more consistent response, more robust reliability, and provisions for other possible uses. I will also develop a new method for reducing error in calibration. A key element of my approach will be to develop fixtures for the fabrication that can produce more reliable bonding between the metal and polymer layers within the transducer.

After some investigation into the causes of variability of these transducers, it was found that the more rigid construction methods did not alleviate many problems. The main success of the new construction method was a decreased failure rate. Calibration, however, was quite successful. Evidence from the data taken in this project points toward a converging value of weighted capacitance. Though the offsets to capacitance due to a heating cycle may be unpredictable, convergence of weighted capacitance values over several heat cycles can certainly reduce error in model magnet stress measurements.

DEDICATION

For Nana and Mamaw

ACKNOWLEDGMENTS

First and foremost, I would like to sincerely thank Andrew Jaisle for the many hours and favors he threw into this project. Without his expertise and input, I would have been completely lost.

I would also like to thank everyone else at the Magnet Lab for their insights and thoughts about my project, especially Al McInturff whose knowledge of the subtleties surrounding stress gauge use in magnets gave the project some sense of direction. Also, a big thanks to my advisor, Peter McIntyre, who invited me to work with the group and suggested the project to begin with. It has been a really great experience. Tim Elliot gave key insight and operated the EDM to cut the stainless steel layers. Akhdiyor Sattarov provided computational data for the ramp rate calculation. And to the rest of the group; Chris English, Raymond Blackburn, Trey Holik, Nate Pogue, Chris Benson, and Kyle Damborsky- thanks for everything.

Finally, I would like to thank Elizabeth and my family for their patience and understanding during the past year and a half. Their support is appreciated beyond words.

NOMENCLATURE

CSG	Capacitive Stress Gauge
SG #X	Xth Stress Gauge Produced
P	Pressure
C	Capacitance
Pa	Pascal (N/m^2)

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CHAPTER I

INTRODUCTION

One of the major goals in developing accelerator dipole magnets is to produce as high a magnetic field as possible. Higher B-fields mean greater particle velocities and more energetic collisions without increasing the radius of a collider. A key difficulty in creating high fields with dipole magnets is that of Lorentz force management. As the magnetic field increases, enormous stresses on the magnet due to Lorentz forces can cause poor magnet performance and even failure. Capacitive stress gauges, or transducers, are used to measure large magnitude stresses in room temperature to cryogenic (~2K) environments where space is at a premium. In this instance, they will measure a few to a few hundred MPa present in the superconducting coil while energized to magnetic fields in the 10 Tesla range.

There have been several hurdles in the development of reliable transducers including connectivity problems arising from shorts while the transducer is under pressure, alignment issues between the individual polyimide/stainless layers which may impact the connectivity or measurement consistency, as well as a multitude of issues concerning the calibration of the transducers as they go through an epoxy curing cycle and are then cooled to about 2K. My goal is to alleviate these problems by developing new fixturing and construction processes which will allow for more robust and consistent transducers.

This thesis follows the style of the *IEEE Transactions on Applied Superconductivity*.

Fixture necessity and development

There are several new fixtures I propose for solving some of the key issues stated above. These fixtures will automate and streamline the construction process and will provide for fewer transducer failures.

Texturing fixture

One of the factors contributing to transducer connectivity issues is that small tears in the polyimide insulating layers develop due to uneven pressure during the abrasion process. The previously used method was to carefully texture each individual polyimide layer by hand with very fine sandpaper. Despite great care being taken to clean all surfaces before each abrasion cycle, holes are still punched through the polyimide creating the possibility of a short between 2 of the stainless layers. The solution to this problem is a fixture that will provide even pressure across the surface of an uncut polyimide strip. It should also allow for the inconsistencies and wearing of the sandpaper to be insignificant factors in polyimide failure with reasonable replacement intervals.

Alignment and epoxy curing fixture

Another factor which contributes to connectivity issues is that of alignment of the polyimide and stainless steel layers as they are prepared for the epoxy cure cycle. The alignment may not be as dire an issue as the pinholes, but without reasonable insulation, the stainless layers may become too close to one another and cause a short. One particular problem arises near the nodes for the measurement devices. The nodes must be bent at 90 degrees so that they do not interfere with other parts of the magnet. The fixture should address the alignment issue as well as be able to gently and consistently bend the nodes to fit the magnet's specifications.

Calibration

The biggest problem facing transducer use is that of calibration. There are two key factors that need to be analyzed as a stress gauge is being calibrated: zero offset and deflection. To examine how deflection affects the calibration curve, a short sample of the coil package must be used. This includes a stack of superconducting cable and a laminar spring. This simulated magnet sample then goes through the calibration with the transducer. As the laminar springs are still under development, my main focus will be on zero offsets and resolving offsets caused by plastic deformation of the polyimide layers during the magnets' epoxy impregnation and curing cycle.

Determining calibration curves and gathering data from the gauges has a two-fold purpose: stress magnitude and distribution verification. Ideally, finite element analysis will give a fair estimate for the real values of stress on the outer coil. The transducers verify that the analysis codes are predicting the forces accurately and whether these forces are being intercepted by the elements that are designed to take them.

CHAPTER II

METHODS

Capacitive transducers are used in model dipoles because they are simple in design, construction, and calibration. Their footprint in the magnet is minimal and interpretation straightforward for force increments. The design is determined based on the specifications of the model magnet. A CSG is a fairly elementary device. It consists of several stainless steel and polyimide layers stacked alternately. CSG’s are essentially several layers of capacitors; simple, planar capacitors. The construction and calibration processes are where the complications arise.

Construction processes

There are several different steps in the construction phase. These steps are outlined below.

Texturing

The polyimide film and the stainless foil are of a very smooth surface finish. The purpose of applying epoxy is to essentially glue each layer together. This can only be achieved when the surfaces of polyimide and stainless are rough. The texturing rig that was developed for this process achieves abrasion without producing pinholes in the polyimide film. The rig is simple; it consists of 2 half-cylinders which are placed very close together with the flat surfaces facing away from one another. The distance between the half-cylinders is adjustable so accommodations can be made for both the stainless and polyimide layers. The adjustments also make it possible to control the pressure applied to the subject layer. Fine grit sandpaper is then taped to each half-cylinder and the polyimide or stainless strip is textured by pulling the length of the strip across the half-cylinders several times. Fig. 1 is a picture of the rig. After the abrasion process is completed, cutouts of the individual layers can be made.

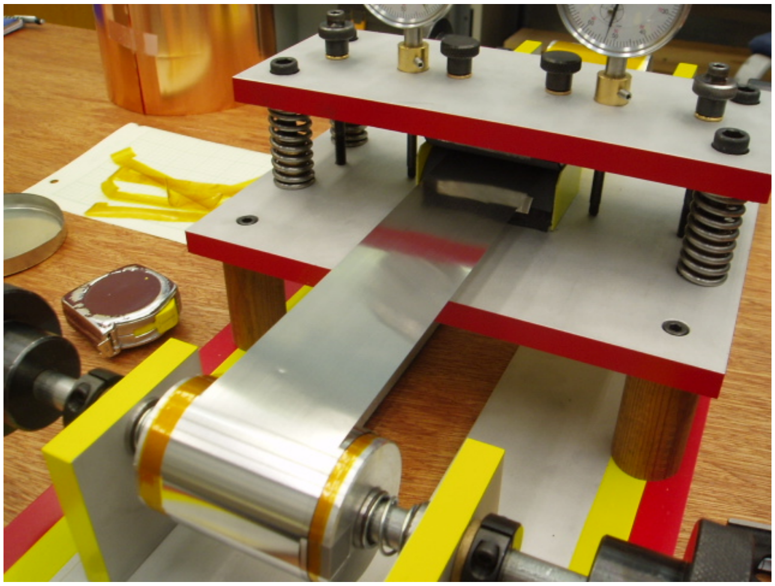

Fig. 1**.** Texturing Fixture. .001" stainless foil is being textured here.

Cutouts: Conductive layers

After abrasion, the stainless layers are cut to size and stacked alternatively with copper foil. This is a necessity since the machine that is used to cut the pieces out (EDM) would weld the stainless layers together while cutting. These layers are compacted, welded on the ends and are then placed in the EDM for cutting. After the cutting, the stainless cutouts need to be cleaned with acetone. Finally, the stainless layers are ready to be used in a transducer.

Cutouts: Insulating layers

The polyimide layers are cut using a simple razor and 2 forms which hold the polyimide in place while the cut is being made. These forms are made out of stainless steel and are in the same shape as the final polyimide layer to be used in the transducer. Cuts are then made with the razor as close to the edges of the forms as possible. Care must be taken when cutting since the blade can get caught and tear, rather than cut, the layer.

Transducer structuring

Stacking each layer of the transducer so that they are aligned requires a fixture. This fixture needs to meet a few requirements: it must keep each layer aligned, it must bend the nodes of the stainless layers so that they meet the specifications of the model magnet, and it must provide for the epoxy cure of the transducer. Fig. 2 is an image of the stacking fixture. Notice the machined surface that holds the transducer in place and the grooves that allow for excess epoxy to flow out of.

The polyimide and stainless layers are stacked alternatively with the nodes of the stainless also alternating from left side to right side. The assembly is then clamped up and prepared for epoxy curing.

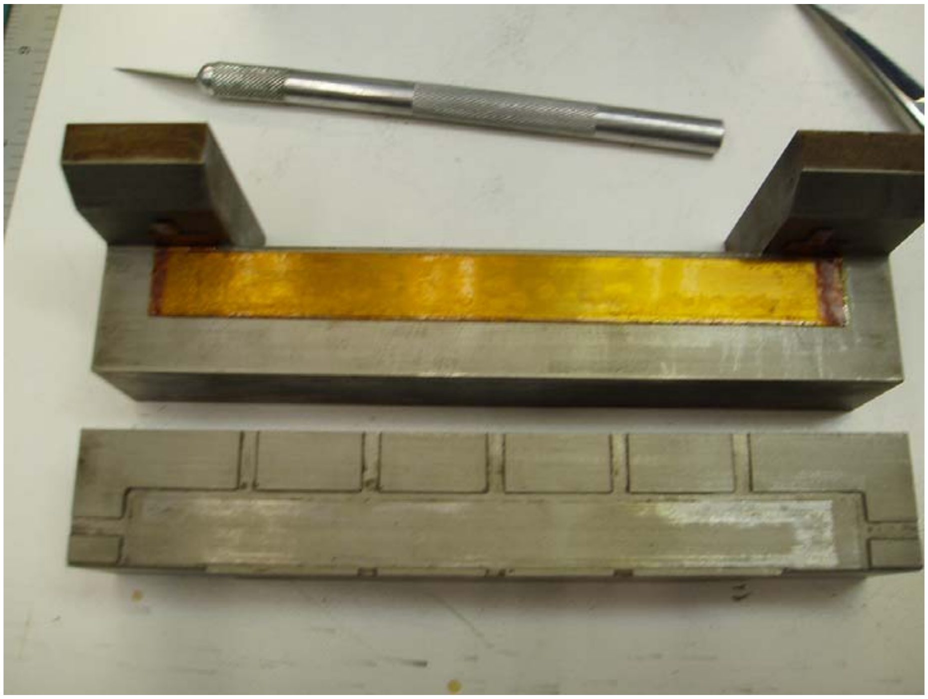

Fig. 2. Stacking Fixture. This transducer (SG #2) has just finished its epoxy curing cycle. The surface of the fixture is sprayed with a PTFE mold release to prevent bonding between the transducer and the fixture. The grooves allow for excess epoxy to seep out as needed.

Testing and calibration

Testing and calibration of the transducers is done by applying a known normal force to the face of the transducer and measuring the capacitance reading as a function of the force. As the force on the transducer increases, the insulating layer is compressed, bringing the conductive layers closer together. The capacitance is inversely proportional to the distance between the conductive layers, but directly proportional to the surface area of the conductor. Multiple layers ensure both a large surface area (increased base capacitance) and a greater amount of polyimide to compress (increased change in capacitance for a given pressure). The upshot of using many layers, however, is a greater risk in including a non-uniform or damaged layer in the transducer package. 7 layers were chosen in consideration of these factors and production time.

The first step is to setup the nodes, wiring them in series. Then, clamp wires onto the 2 end nodes. These wires are connected to a LCZ meter which will measure the capacitance. A fixture is needed to help in the compression process, so as to distribute the force of the press evenly across the entire transducer. This simulates the way that pressure will be distributed during the model magnet testing. To further simulate magnet testing, the temperature of the transducer needs to be lowered to 77K. The magnet will be tested at much lower temperatures; however, the mechanical and electrical properties of the polyimide, stainless, and epoxy vary much more dramatically in the transition from 300K to 77K than from 77K to 2K [1]. This is also true for the calibration curves. The compression fixture is then put under pressure. Calibration curves are acquired by varying the applied force and plotting it against the measured capacitance. The process is not straightforward, since there is some plastic deformation of polyimide during the magnet's epoxy impregnation and curing cycle. I will be simulating the process of the transducer being taken through the magnet's epoxy cure cycle to determine whether there is a finite heating training period for the transducers.

CHAPTER III

RESULTS

The results are compiled similarly to the way that the methods section is above.

Construction processes

This section is devoted to a critique of the construction processes as practical methods for mass producing uniformly functioning transducers.

Polyimide and stainless texturing

The new texturing fixture we developed has been very successful within the scope of this project. Whereas previous methods of abrasion and texturing have produced inconsistencies on the surfaces of each layer and, in many cases, tearing of the .001" thick polyimide layers (see Fig. 3), there have been no such issues surrounding the new texturing process. The polyimide and stainless steel layers are fairly uniform with few inconsistencies to speak of. Even with the abuse of 30+ texturing cycles, strips of .001" thick polyimide show very few signs of tearing or any other major damage.

In addition to consistently producing reliable layer materials, the new texturing process and fixture have greatly increased the rate at which these layers can be prepared. Within 20 minutes, it is possible to texture enough polyimide to produce 4 transducers. This is a huge improvement compared to the painstaking task of texturing each layer individually.

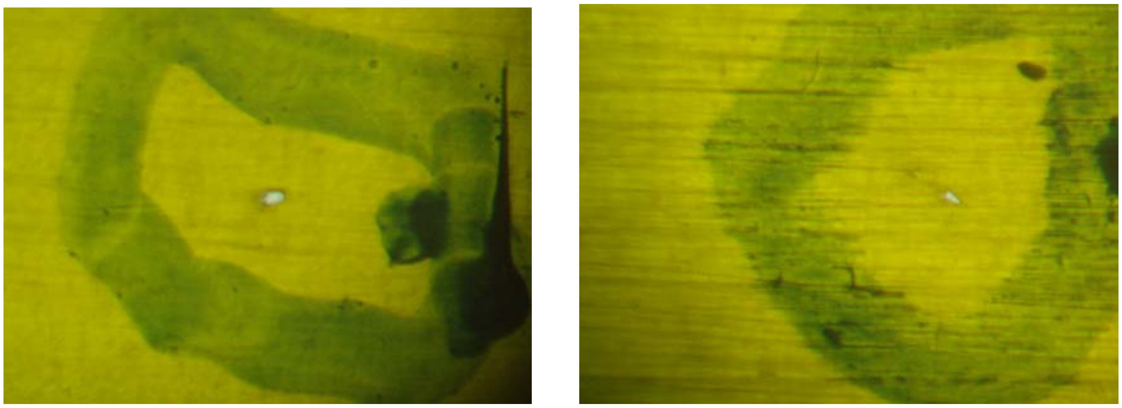

Fig. 3**.** Polyimide Layer Tearing. These are pictures of .001” thick polyimide after an abrasion-by-hand test, magnified 30x. Notice the small tears in these layers. The texturing fixture we developed greatly diminished the frequency of these “pinholes.”

Polyimide and stainless cutouts

There are some lingering issues here surrounding the cutout process that was used for the polyimide layers. In using the "clamp and cut" method described in Chapter II, we found tearing along the freshly sliced edge due to the blade pulling the polyimide instead of cutting it cleanly. This occurred with frequency even when preventative measures, such as regular blade changes and increased clamping pressure on the plates, were taken. We experienced edge tearing for both the .002" and .001" thick polyimide.

The stainless steel layers were cut out by EDM and had essentially no problems in their manufacture. Of course, typical machining issues arose in a limited fashion. For example, there was uneven heating and even some welding that occurred between layers of stainless being cut. These events were rare and did not cause any kind of production hold up. One important process to emphasize here is the deburring of the cut stainless layer edges. We found that significant damage can occur to the thin polyimide layers as a result of clamping them to stainless steel layers which were not deburred. This damage would assuredly cause a short and ruin the otherwise well constructed transducer.

Stacking and bonding

In relation to all other processes, our methods of layer stacking and adhesion are, by far, the most problematic of the construction processes. During the stacking process, there were several competing factors that made the fabrication by hand fairly difficult and irreproducible. The first issue that was encountered was the inability of the bottom polyimide layer to stay within the mold of the fixture. We dealt with this problem by gluing the bottom layer to the fixture, then cleaning the fixture before the epoxy curing cycle. If the fixture is not thoroughly cleaned and is without a mold release agent (we used a PTFE based mold release, which worked well), the bottom layer will bond to the fixture and the transducer will have some layer tearing as it is pulled from the fixture. This was the main issue with SG #1.

Also worth noting is the likely damage that the .001" polyimide layers will acquire due to the rough stacking process. The layers must be stretched tightly and readjusted several times due to the small amount of tolerance between the layers and the fixture. The motivation behind developing the texturing fixture was to minimize the damage caused to the thin polyimide strips. The stacking process is the most damaging to these layers thereby negating the care taken in the texturing process.

Calibration and testing

There are many interesting properties surrounding capacitive stress gauges and their calibration. I focused on aspects that would be most instrumental in understanding how CSG's should be implemented in the TAMU III magnet.

Creep effect

One property of the CSG's that was immediately recognizable is that of a finite response time. As pressure is applied to the transducer, the polyimide deforms and compresses, increasing the capacitance. This process is not only dependant on the magnitude of the pressure, but also depends on the rate at which the pressure is applied. This "creep" effect can be seen on Fig. 4.

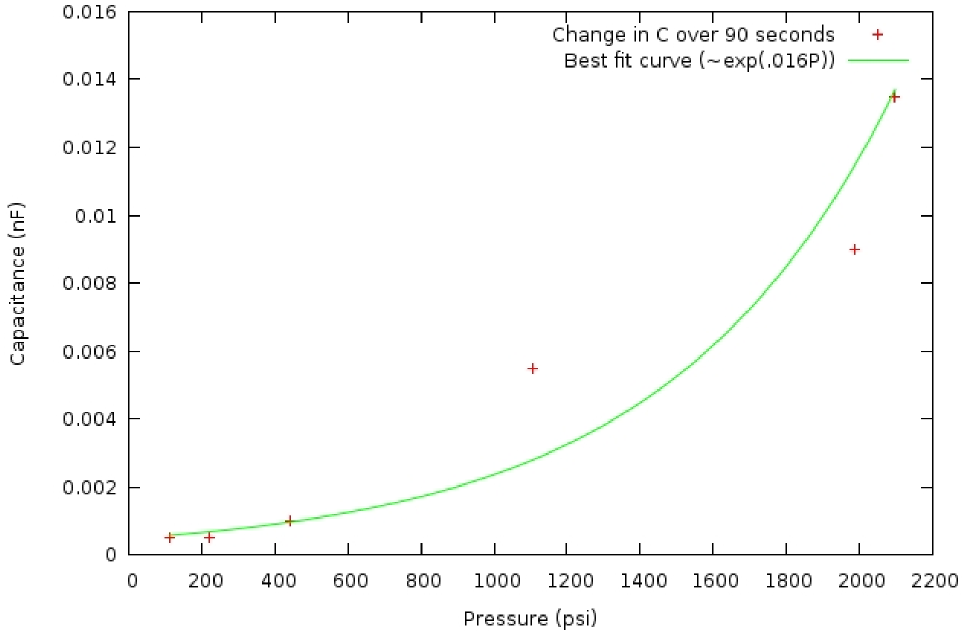

Fig. 4. The Creep Effect. The points are the change in C for a given interval increase in P over a 90 second period. The green curve is a best fit curve for the 6 points taken.

Essentially, what Fig. 4 shows is that there is an exponentially increasing shift in initial capacitance measurement as the change in pressure per unit time increases. Since this relationship is non-linear, there is not a constant creep background and errors can dramatically influence results. This becomes especially true at high end pressures, since the error will propagate and sum at those later times. I have calculated a reasonable ramp rate that will make the error negligible for the pressure range that the magnet operates at. The rate of pressure change should be at or below 4.4 psi/sec, or a corresponding current of 200000A/sec for the error to remain negligible.

Pressure calibration curves

Fig. 5 is a set of pressure calibration curves for SG #2 and Fig. 6 is a similar set for SG #3. These are both pre-heat cycle. Fig. 7 shows how these values converge.

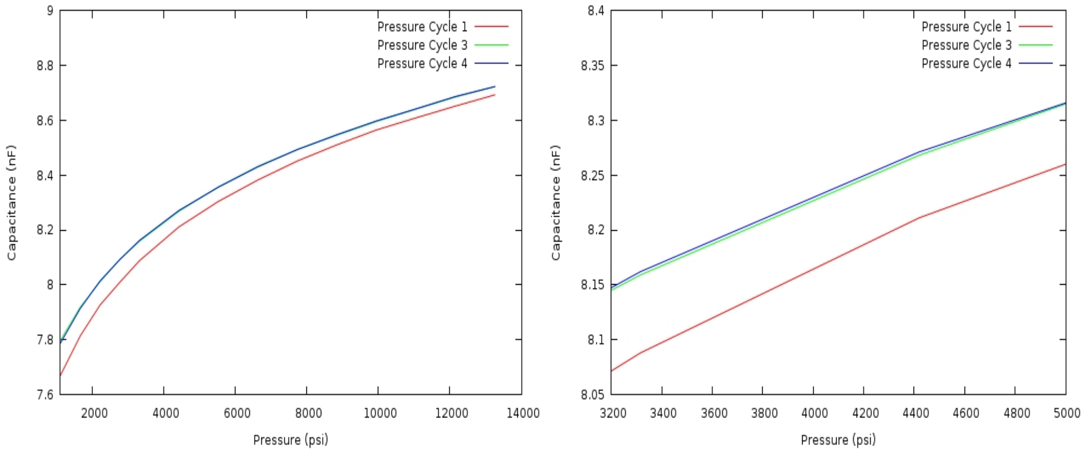

Fig. 5. Calibration Curves for SG #2 Pre-Heat Cycle. The graph on the left shows the general behavior of a calibration curve. The graph on the right shows how convergent these calibration curves are on just the 3rd and 4th pressure cycles (green and blue, respectively).

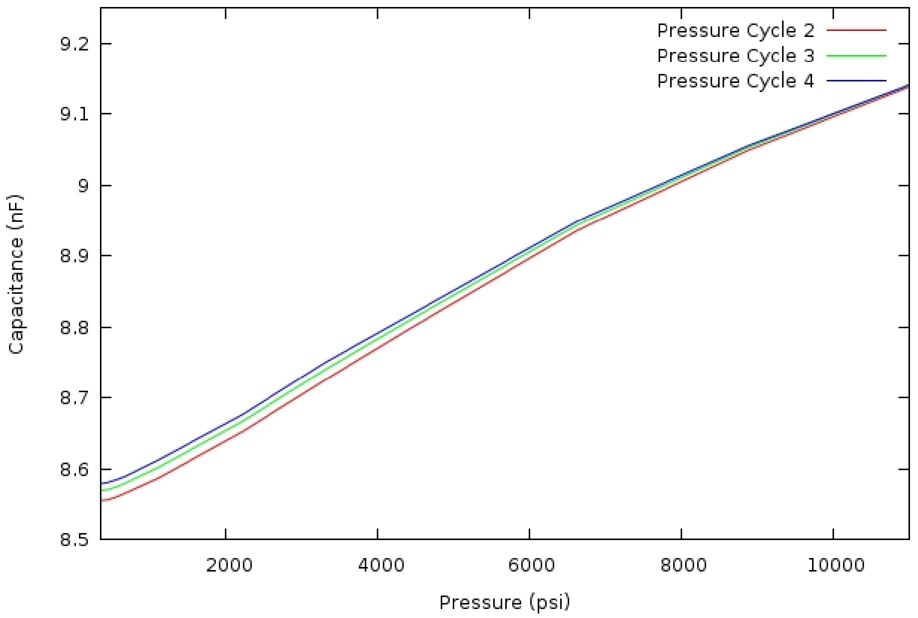

Fig. 6. Calibration Curves for SG #3 Pre-Heat Cycle. This is a similar plot to Fig. 5 except that the pressure range is smaller and the resolution is much higher (~100 psi).

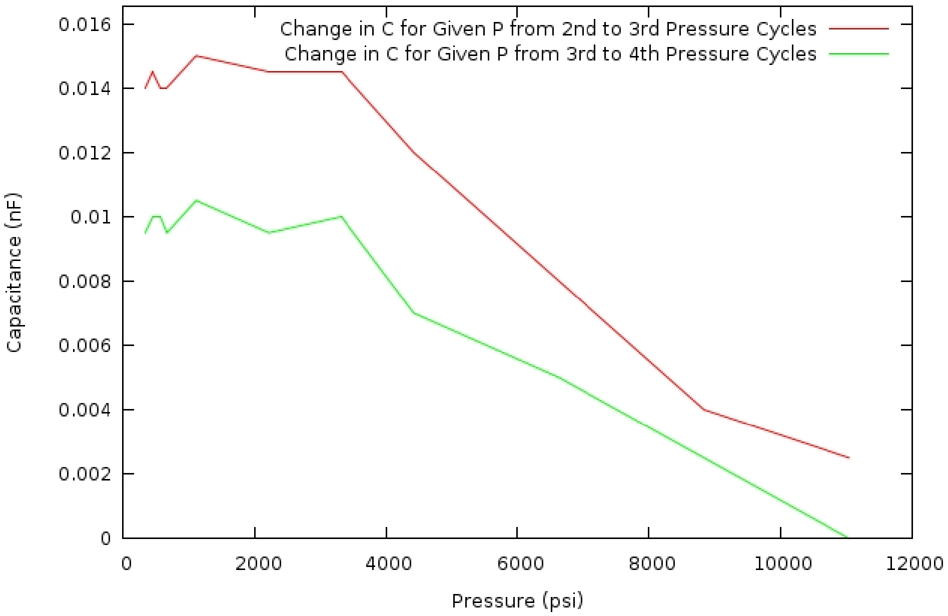

Fig. 7. Change in Calibration Curves Between Subsequent Pressure Cycles for SG #3. Note that after 4 pressure cycles (green), the calibration curves converge to within 10 times the resolution of the multimeter. At this rate, the difference between 2 subsequent curves becomes negligible near the 10th pressure cycle.

Pressure cycling post heating cycle

As expected, loading the transducer and putting it though the magnet's epoxy cure cycle changed some properties. The heating cycle also diminished the effects of previous pressure training and offset the calibration curves significantly. There were some properties that were comparable, starting out with the overall behavior of the calibration curves as well as their convergence properties. Fig. 8 is very similar to Fig. 5 above; they are the same plots except the data was taken after the first heating cycle of SG #2.

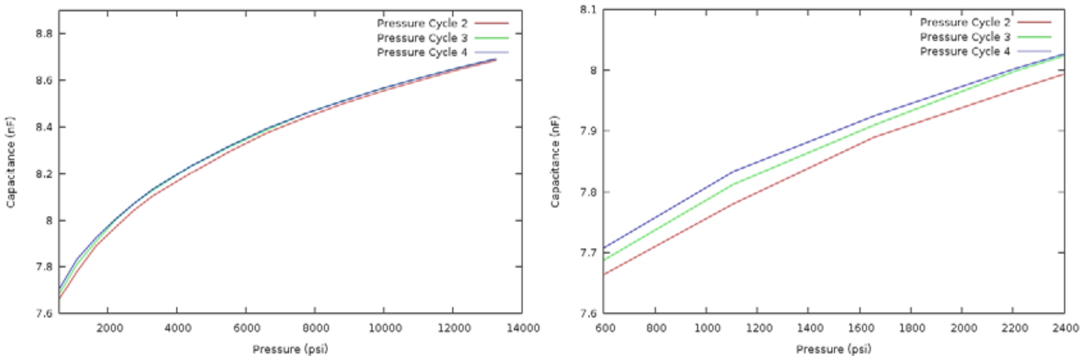

Fig. 8. Calibration Curves for SG #2 Post-Heat Cycle #1. Similarly to Fig. 5, the left plot shows the general calibration behavior and the right plot is a detailed view of the convergence of calibration curves for a smaller interval.

It is important to note that the heating cycle does not significantly alter the convergence of the calibration plots. For SG #3, similar properties were retained. Figs. 9 and 10 are analogous to Figs. 6 and 7 and show that the pressure convergence occurs in the same fashion post-heat cycle.

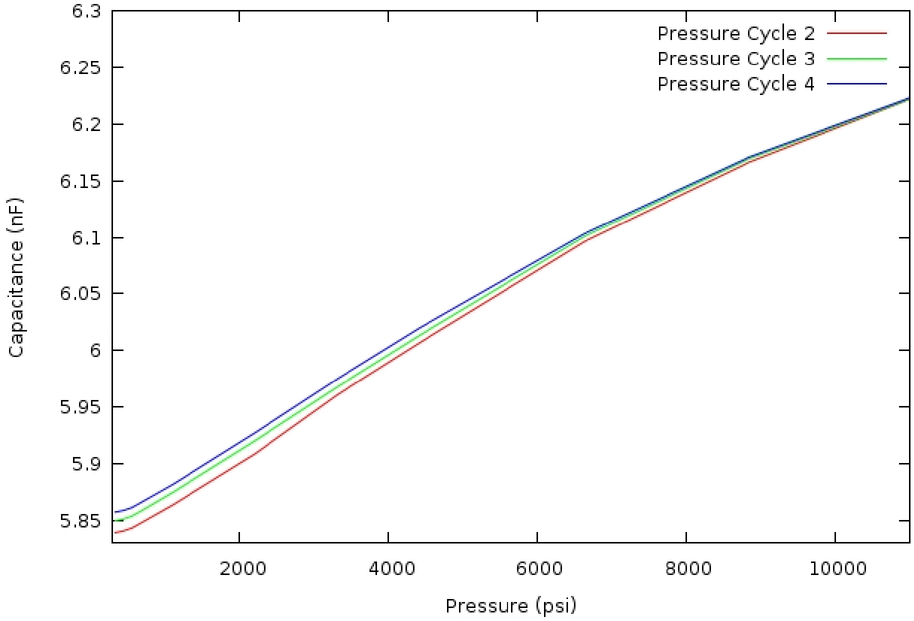

Fig. 9. Calibration Curves for SG #3 Post-Heat Cycle. Notice that the relative behavior of these curves mirror the behavior of the curves for the corresponding Pre-Heat Cycle (as in Fig. 6), even though there is a large offset in capacitance value.

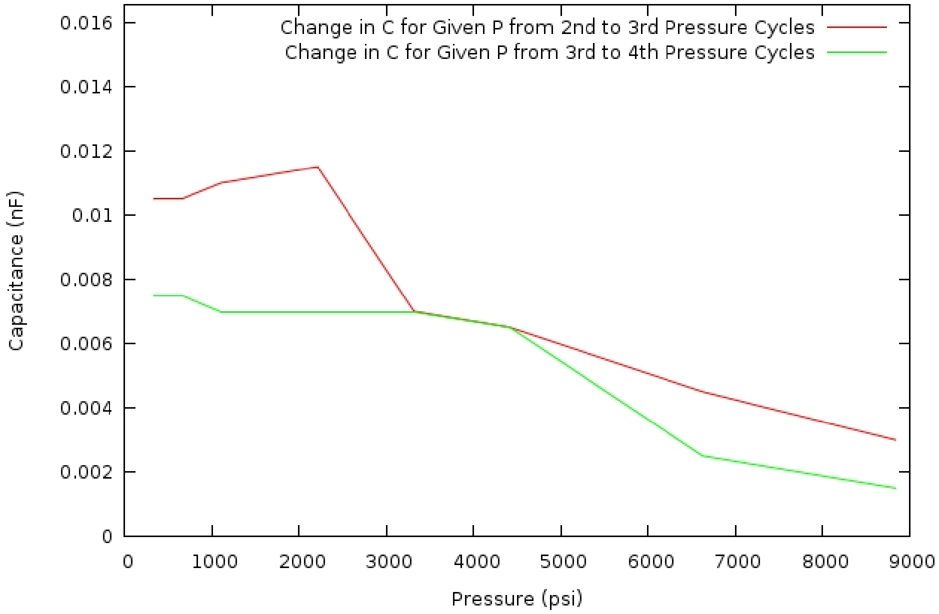

Fig. 10. Change in Calibration Curves Between Subsequent Pressure Cycles for SG #3 Post-Heat Cycle. These general behaviors and magnitudes roughly replicate the behaviors and magnitudes of SG #3 pre-heat cycle (as in Fig. 7).

As the previous figures suggest, there is a consistency of pressure calibration convergence rates, even over several heat cycles. Calibration curves will converge at the same rates once the transducer is implanted into the model magnet. When testing begins, the transducers should have stable P vs. C curves at the end of the model magnet's training.

Heat cycle training

Although the general pressure cycling of the calibration curves is only slightly affected over several heating cycles, the zero-offset and overall shapes of these curves is not preserved. In fact, raw data analysis was unsuccessful in determining a relationship between the number of heat cycles and the convergence of the pressure trained calibration curves. It is possible to show convergence over heat cycling, however, by examining weighted, or normalized, capacitances. By dividing all values of C for a given heat-cycle trial by the value of C at a given pressure, the convergence becomes clear. The true downfall of this process as a method to determine true values of pressure is that any information on the zero-offset is lost. Fig. 11 shows calibration curves pre-heat cycle and after the first and fourth heat cycles. Fig. 12 is the average difference between calibration curves of different heat cycles.

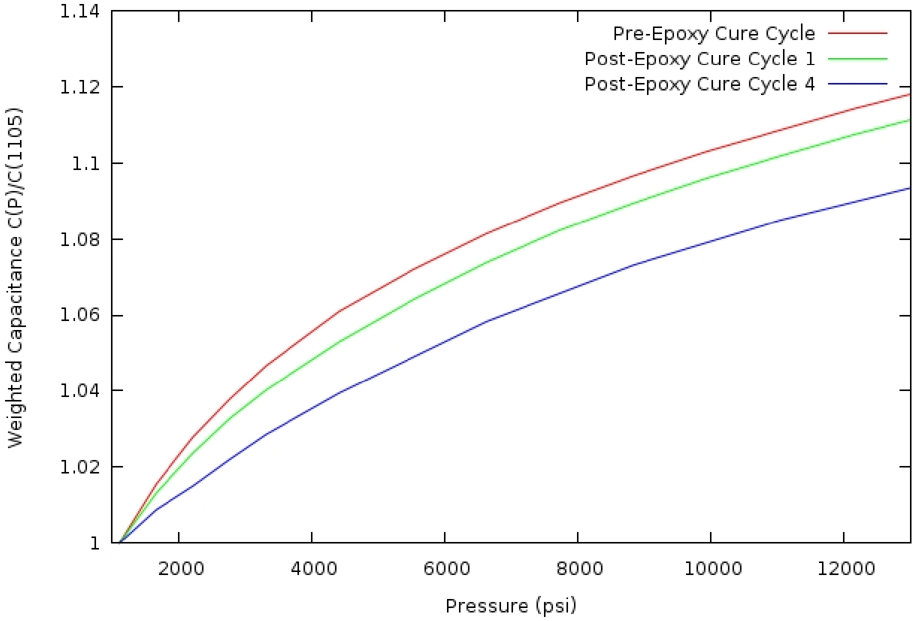

Fig. 11. Weighted Calibration Curves Over Several Heat Cycles for SG #2. All curves are normalized at P=1105 psi. Notice that the lowest curve (blue) is the curve for post-heat cycle #4.

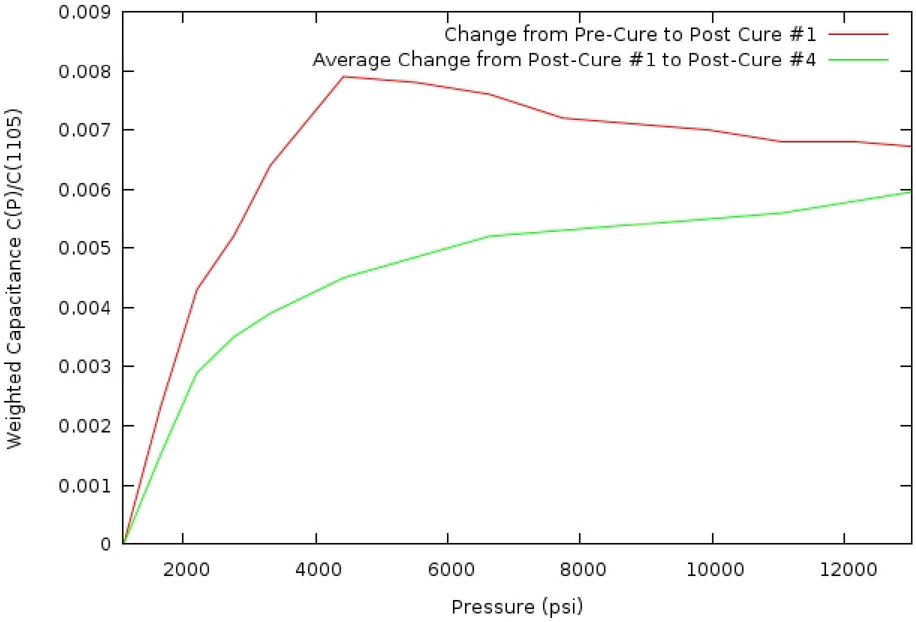

Fig. 12. Average Change in Weighted Calibration Curves Between Various Heat Cycles for SG #2. There is clear convergence of the calibration curves as the transducer goes through multiple heat cycles.

Although analogous data was not taken for SG #3, the results from a couple of preliminary trials look promising. Fig. 13 is a plot similar to Fig. 11 for SG #3. It is not possible to determine whether there is convergence for this data, but the change in weighted calibration curves from the pre-heat cycle to post-heat cycle #1 looks similar to that of SG #2.

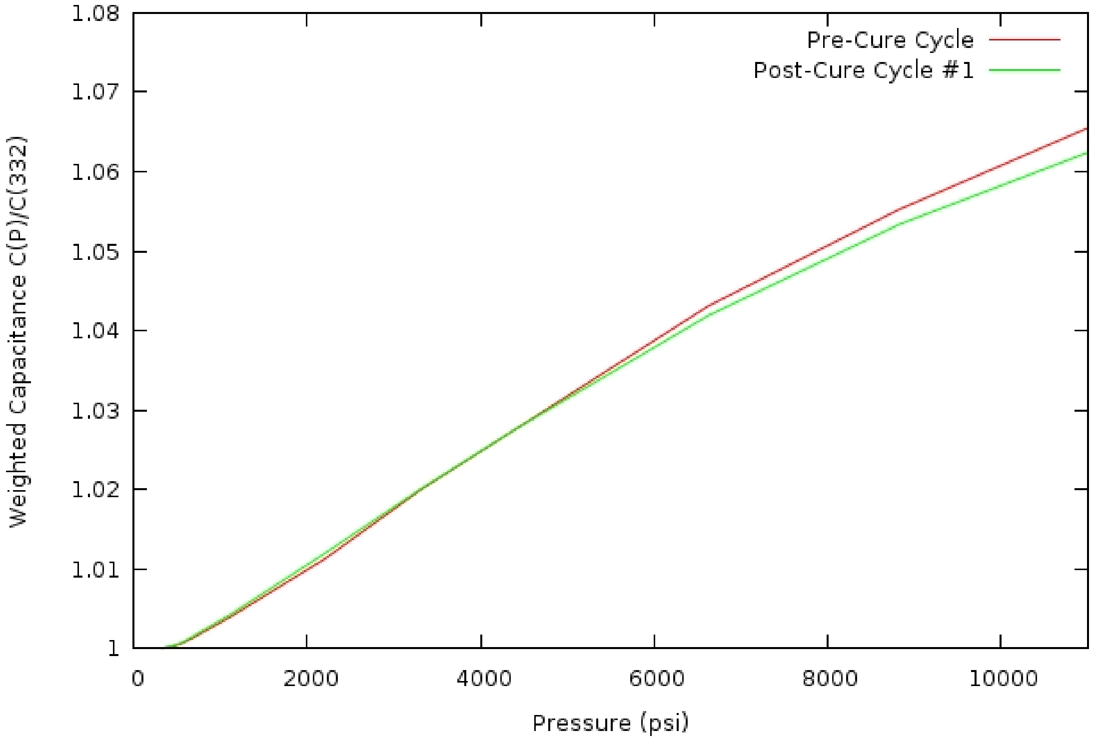

Fig. 13. Weighted Calibration Curves Over Several Heat Cycles for SG #3. Similarly to the weighted calibration curves for SG #2, there is an overall decrease in the curve (at higher end P) for the subsequent heat cycle. The decrease for SG #3 is smaller than that for SG #2 which suggests that SG #3 might converge more quickly.

CHAPTER IV

SUMMARY AND CONCLUSIONS

The promise of a uniformly working set of capacitive stress gauges is still unrealized. While the new construction methods have helped in the fabrication of uniformly textured layers and working transducers with a low failure rate, there are still several processes that must be automated and controlled to produce transducers with consistent properties. Epoxy application and layer stacking are the main suspects in transducer non-uniformity. For a future project, I would suggest a couple of changes be made for these processes.

Although the epoxy used to bond the layer surfaces becomes viscous as it goes through the curing cycle, it is not viscous enough for irregularities to be stamped out completely. “Painting” the epoxy on the surfaces with a brush is simply too haphazard. This non-uniformity is propagated as more layers are stacked and bonded, leaving the final transducer unique and irreproducible. I suggest using some sort of spraying method to more evenly distribute the bonding agent. This would not only make the transducers more uniform, but would also reduce the epoxy thickness (meaning less effect on the transducer’s bulk modulus).

Another culprit in transducer non-uniformity arises from the stacking process. While the indentations provide decent guides for polyimide layer alignment, they fail in providing a way of lining up the stainless steel layers. I suggest a new type of fixture to provide for more consistent package alignment. The fixture would consist of 2 main components which would have mating surfaces. Each surface would hold a layer (or many layers), and, with a rail guiding system, the 2 surfaces would mate. As pressure is applied, the polyimide/stainless layers will bond together. This method gives much more control and provides a known tolerance for transducer dimensions.

We were also able to determine some useful concepts and quantities. By measuring the creep in capacitance as pressure was applied over a time interval, it is now possible to set a maximum ramp rate for the magnet when it is tested. Without this knowledge, the limitations of the pressure ramp rate of the CSG's would be unknown and errors would be unaccounted for at very high ramp rates. In general, however, the maximum transducer ramp rate is much larger than the maximum magnet ramp rate.

Also, the calibration of the transducers is now better understood. One of the main requirements imposed is that the calibration curves of the transducers must converge during the training cycles of the magnet. This could be as few as 10 ramp cycles. This project was able to develop CSGs that had adequately converging properties within 6-8 pressure cycles.

Without other considerations, the zero-shift due to an applied heat/cooling cycle is unavoidable and somewhat unpredictable. In terms of determining pre-load stresses accurately on their own, these transducers have failed dismally. We are, however, able to determine pre-load stresses via deflection. The laminar spring has been implemented to keep a certain amount of pressure on the magnet, even as it cools to 2K. Using the deflection of the spring in the cold magnet, it is possible to determine that pressure.

As a consequence of knowing the pre-load pressures, a new method for reducing error in calibration has been proposed. It can be shown that there are convergent properties as the transducers are put through several heat cycles. Plots of the weighted capacitance, or ratio between capacitance and pre-load capacitance of a given heat cycle, showed that calibration curves do converge over a reasonably small number of heat cycles (good convergence over 7-10 cycles). The implementation of weighted capacitance and heat-cycle training provides post-testing analysts a method to further reduce error in the pressure measurements.

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