THERMAL FATIGUE TEST APPARATUS FOR LARGE SUPERCONDUCTING COILS

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ABSTRACT

The United States Navy has a continued interest in the development of High Temperature Superconductivity (HTS) to provide power dense, efficient propulsion and electrical power generation. These machines have large HTS rotor coils that will undergo many thermal cycles during the life of the ship. Thermal fatigue tests for large coils are necessary to understand any degradation and life issues that could arise. The Naval Surface Warfare Center Carderock Division (NSWCCD) has sponsored Rowan University to design and build a device that will assist in the thermal fatigue testing of a superconducting coil. It was designed to be autonomous with programmable cool down and warm-up rates and varying temperature from ambient temperature (300K) down to 77K. A typical test would include thermally cycling a coil a specified number of times, then performing a critical current test on the coil and repeating the test cycle as many times as desired. This paper introduces the thermal cycling test setup and presents preliminary calibration data.

KEYWORDS: Superconducting coil, thermal cycle, motor, generator, thermal fatigue.

INTRODUCTION

The advent of effective high temperature superconducting (HTS) wire has lead to a variety of attractive applications within the Navy. Superconductivity enables higher power density among machinery applications which support the overarching goal of the Navy to move toward an all-electric ship. Typically modern day superconducting motor applications make use of the tape form of BSSCO or YBCO wound in coil form and

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secured in an epoxy potting process [1, 2]. This leads to a majority of rotating machinery applications that use flat pancake or racetrack coils. Ideal use of a superconducting machine would be to maintain a permanent state of cryogenic temperature in the superconducting part of the machine; however ships have historically been used in manners not within the original condition of operation. Even though it may take a period of a few days to warm up or cool down a particular superconducting machine, this thermal cycling effect should be considered and any possible degradation in performance should be known.

Typical HTS machine applications operate around 30K which is an optimized temperature when considering cost, size, and performance but does not lend itself to a low cost, abundant liquid cryogen. Liquid nitrogen (LN_2) at a temperature of 77K, presents a much more economical cryogenic temperature for thermal fatigue testing. Nitrogen is plentiful, inexpensive, and easily generated in-house. For this reason, it was decided that an automated thermal fatigue platform would be developed using LN_2 at the cold end.

APPARATUS DEVELOPMENT

Concept of Apparatus Operation

The Navy wanted the ability to thermally fatigue-test large coils in a cost effective manner including initial procurement as well as direct test costs. For this reason, it was decided to use a large LN_2 dewar flask which was available. This dewar has an inner bore of 76.2 cm with a depth of 183 cm. A test coil would be lowered into a bath of liquid nitrogen a number of times. Then a critical current test would be preformed to evaluate superconductor performance.

A few assumptions went into the development of this setup. The dewar, when partially filled with LN_2, would create a smooth temperature gradient from ambient to 77K. An HTS coil could be lowered into this temperature gradient at a rate much slower than the time required for the coil to achieve a uniform temperature. This cool down rate would also be some value of interest, especially as compared to the calculated maximum cool down rate specified by the manufacturer, or the maximum cool down rate achievable by the cryogenic system supporting the superconducting device. The generally expected temperature profile is shown in FIGURE 1.

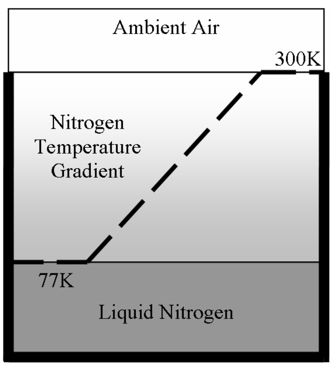

FIGURE 1. This figure shows a fundamental assumption as to the temperature profile that would be present in a dewar flask with LN_2 in the bottom and ambient condition at the mouth of the flask.

FIGURE 2. (Left) This image shows the mechanical setup of the lowering mechanism including the stepper motor connected to a 50:1 worm gear reducer and the stepper motor controller electronics. (Middle) Lowering platform made of G-10 capable of holding a 76.2 cm racetrack coil. (Right) The thermal cycle test apparatus.

Ideally this temperature profile would be linear and a simple open loop control architecture such as lowering the coil into nitrogen at a uniform linear speed would work well. However due to temperature dependent changes in thermal conductivity or any convection currents enabled by the large diameter of the dewar, this may not be the case. Instead a control algorithm which controls based on temperature change will achieve a higher level of control.

Hardware

To achieve the desired capability of controlling the cool down rate of a large HTS coil, a support rig had to be developed, along with a suitably sized motor and gear train capable of handling heavy weights. The test frame, 122cm x 122cm x 305cm, was constructed of 4.13 cm slotted strut channel large enough to fully enclose the dewar. A high torque (9 N-m) stepper motor connected to a 50:1 worm gear reducer, shown in FIGURE 2, was mounted at the top of the frame. This setup provides excess capability even when testing a load of 135 kg. A 6.35 mm stainless steel cable is used to connect the mechanical drive system to the lowering platform. The lowering platform is made of G-10 in an open design to allow minimal restriction to heat flow while still being sufficiently strong to support up to 135 kg.

In order to control the stepper motor, a National Instruments (NI) PCI-7332 stepper motor controller was installed in a host computer. Since NI does not have a motor drive that would fit the specification of the stepper motor, a universal motion interface(NI UMI-7754) was used to bridge the gap between the stepper motor controller and a different manufacture's drive. A Compumotor Gemini GT-L5 stepper motor drive was used which exceeds the 3 amp requirement of the stepper motor.

An NI USB-6210 data acquisition board was incorporated to read the DT-470 silcon diode sensors attached to the lowering platform. The interface for all these components was incorporated into a single host PC.

Software

A front end solution was developed in LabVIEW to implement the closed loop control algorithm as shown in FIGURE 3. It was desired for this graphical front end to be user friendly with a variety of configuration options. Total autonomy was developed to

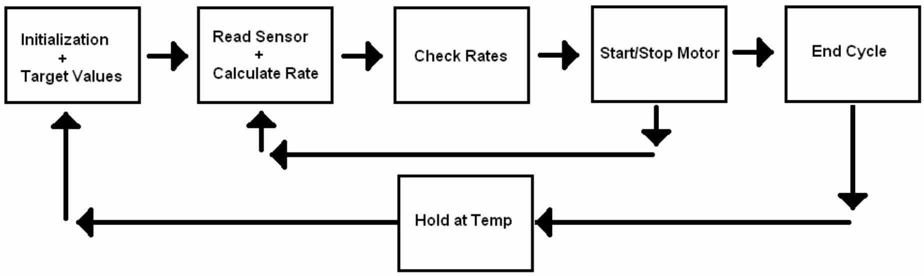

FIGURE 3. This diagram depicts the closed loop control algorithm implemented in LabVIEW which uses sensory input to determine motor control output.

allow a certain number of thermal cycles to elapse as a specified cooling or warm up rate was maintained. The program is set up to allow the user to specify a hold position at ambient or cryogenic temperatures. This is required for multiple thermal cycles before a critical current test is performed. The user interface displays current temperatures of the lifting platform as well as instantaneous temperature rate of change.

A dropping distance of 198 cm is achieved by controlling the number of steps it takes the stepper motor to produce that distance. There is no other form of position feedback to this system. If the motor were to slip a few steps, it would no longer return to the proper calibrated start position or the fully lowered position. However since the dropping distance is equivalent to approximately 88,000,000 steps, a slip of a few motor counts would have a negligible effect.

The primary purpose of this algorithm is to control the coil cool down rate. Twenty temperature readings are averaged to formulate a single temperature point in time, and eliminate noise from the sensor reading. A second data point is taken during the next program iteration and is used in conjunction with the time difference between iterations to determine the cool down rate. If the cool down, rate exceeds a value pre-set by the user, the program halts the stepper motors motion until the rate is no longer exceeded. Implementation of the above approach provides an effective control for the rate between any two data point readings. However, if the rate was excessively exceeded, there was no additional pause in motion beyond a single iteration stall. The algorithm was tweaked through motor speed and acceleration control until the instantaneous rate spike was absorbed into surrounding rates through very gradual motion changes.

CALIBRATION AND TESTING

Test Coil Fabrication

A fundamental assumption in the development of this test apparatus was the concept that the coil would be lowered into the nitrogen at such a slow rate that uniform coil temperature would be achieved. To test this assumption a coil was created and instrumented with 12 type T thermocouples. The coil served no other purpose than to act as a representative thermal mass with properties similar to what would be seen in an actual HTS coil. For ease of creation, the coil was made from scrap copper-coated low

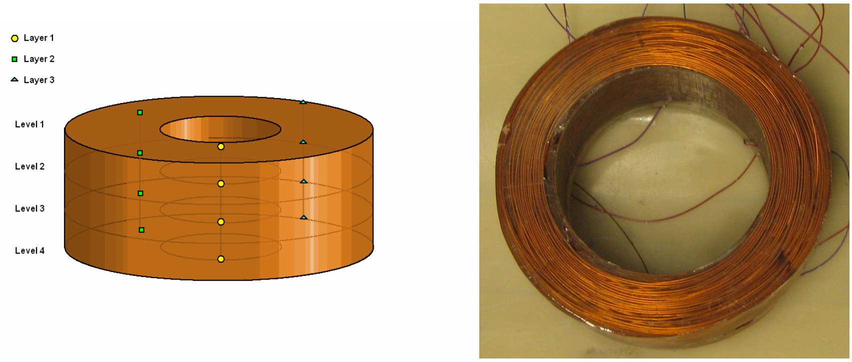

FIGURE 4. Instrumented low temperature superconductor coil with type T thermocouples located on the inner radius, mid radius, and outer radius of the coil with 4 equally spaced axial level of sensors.

temperature superconductor and was wound by hand around a mandrel. During the winding process twelve type T thermocouples were placed at four different heights and three axial distances in the coil as depicted in FIGURE 4. The coil was then vacuum encapsulated in epoxy. No additional machining of the coil was performed after the potting process.

Calibration Testing

14 thermocouples spaced 15.25 cm apart were installed to provide a vertical temperature profile within the dewar. The test coil was mounted to the center of the lowering platform such that the two platform temperature sensors were located immediately below and above the coil. The dewar was filled with approximately 25 cm of LN_2 at the bottom of the dewar in order to fully submerge the test coil and platform. A separate computer equipped with a data acquisition board was used to collect the coil and dewar temperatures.

The temperature profile within the dewar is shown in FIGURE 5. Its non-linear nature demonstrates why a constant speed control would not produce a constant cool down rate.
A test was established to evaluate the uniformity of temperature within the coil as it was lowered. A pre-set cooling rate of 180K/hour produced the resulting coil temperatures

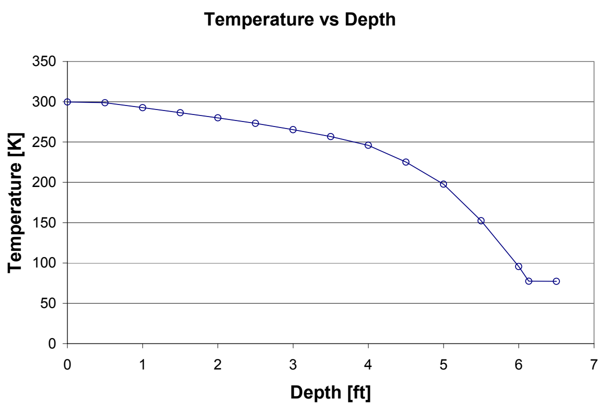

FIGURE 5. This graph shows the steady state temperature profile in the dewar.

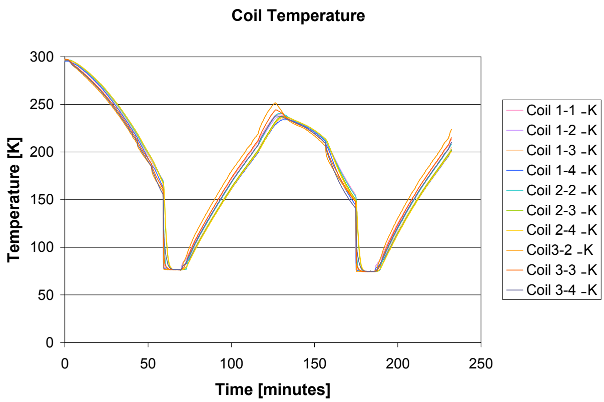

FIGURE 6. This graph represents coil temperatures over time as it descends into the dewar at a rate of 180 K/hr.

shown in FIGURE 6. Temperatures within the coil remained uniform to within an average spread of 14K, including those recorded during a rapid descent into the nitrogen. During an earlier rapid immersion into the liquid nitrogen, spatial temperature variations almost 3 times this amount were observed. As a result, the algorithm was adjusted to gently ease the coil into the LN2 bath thereby avoiding large temperature gradients in the coil.

Temperatures measured during a cool down at the rate of 360 K/hr are shown in FIGURE 7. The cool down rate at different locations is offset in the time domain due to small gradients present in the upper and lower platform temperatures. The cool down rate of 360 K/hr is maintained from the beginning of the test through the actual immersion into liquid nitrogen. The warm-up portion of this cycle proceeds more slowly (228 K/hr) due to the significant thermal mass of the coil. FIGURE 7 also displays a feature of the control algorithm that halts the motion of the platform when the lower sensor reaches the liquid nitrogen. As a result the coil temperature avoids an excessively rapid cooling rate and possibly harmful internal thermal stresses.

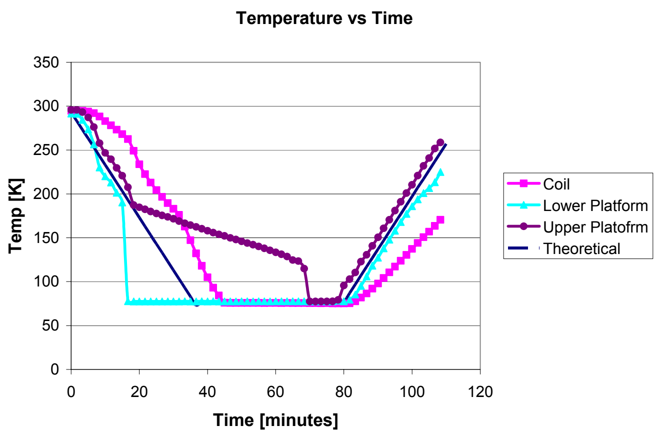

FIGURE 7. This graph shows the coil cool down rate in relation to the program specified rate.

CONCLUSION

A thermal fatigue test apparatus was developed and tested. This apparatus is able to autonomously thermally fatigue a superconducting coil up to 76.2 cm in diameter from ambient condition to 77K while maintaining a specified cool down rate. Critical current tests can be manually performed after a specified number of thermal cycles.

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