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Characterization of MEMS Acoustic Sensors and Amplifiers in Cryogenic Fluids for Quench Detection Applications in HTS CICC

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***Abstract*— An acoustic quench detection method utilizing MEMS (Micro Electro-Mechanical System) acoustic sensors is proposed. To investigate this method, a commercially available MEMS piezoelectric microphone, the Vesper VM1000, and two types of second stage amplifiers, using either an OPA344 or a LMH6629 based amplifier circuit, were characterized at cryogenic temperatures in helium gas. The MEMS microphones were in their original package with an integrated preamplifier. The tests were performed inside a two-stage Gifford-McMahon cryocooler from room temperature down to 60 K, at static pressures between 1.2 and 1.4 bar in gaseous helium, over the frequency band from 100 Hz to 10 kHz. Second stage amplifiers were needed to achieve signal to noise ratios approaching the manufacturer specified operating levels. The OPA344 based amplifier reduced in gain by >55 dB below 230 K, while the LMH6629 based amplifier performed well down to 60 K. The MEMS microphones appear to perform acoustic measurements down to 165 K but with some reduction in sensitivity down to 60 K. An acoustic model of the cryocooler plane wave tube calibration setup is developed and used to calibrate the microphone despite the presence of a significant thermal gradients down the plane wave tube.**

***Index Terms*— Quench detection, MEMS sensor, acoustic sensor, superconducting magnet, cable-in-conduit-conductor (CICC), HTS, REBCO.**

I. Introduction

High temperature superconducting (HTS) tapes are attractive materials for high field and high current superconducting magnets due to their excellent mechanical properties and high current density with high magnetic field.

To protect superconducting magnets and ensure safe operation, various quench detection methods have been developed, mainly for low temperature superconductor (LTS) applications. Those methods include: electric voltage detection [1], optical fiber temperature detection [2]–[4], active acoustic temperature detection in solids [5], hydraulic pressure and flow detection at an inlet and an outlet of cable in-conduit conductor (CICC) [1], [6], and acoustic emission (AE) detection to detect acoustic signals generated by cracking, delamination and rapid temperature changes[7]–[9], and magnetic flux change detection [10]–[12]. When a quench occurs in a HTS application, the normal zone propagation velocity is two to three orders of magnitude lower than the one of LTS material [13]–[17], therefore the normal zone is confined in a small area. An immediate consequence of the lower propagation velocity is that a very sensitive method to detect and locate the quench is necessary.

An alternative acoustic quench detection method detects pressure waves in the coolant space using MEMS (Micro Electro-Mechanical System) acoustic sensors [18], [19]. In this method, a linear array of MEMS acoustic sensors is mounted in the coolant space of a forced-cooled CICC. When a quench occurs, the heat generated by the superconductor dissipates into the coolant, and therefore vaporizes liquid coolant or expands gaseous coolant. An acoustic pressure wave caused by the change in temperature and hydraulic conditions can be detected by the MEMS sensors. This wave travels at speeds on the order of 100 to 1000 m/s in cryogenic helium or nitrogen, three orders of magnitude or more above the normal zone propagation velocity in HTS conductors.

This method is therefore particularly suited for HTS conductors since it can provide high detection speed, good sensitivity, and the ability to localize quench event. Previous experimental studies have shown a MEMS piezoelectric microphone sensor may be able to sensitively and quickly detect the quench event of single HTS tape in liquid nitrogen environment [19]. However, no characterization data is available for cryogenic operation of commercially available MEMS microphones which would be attractive for this application due to their low cost and

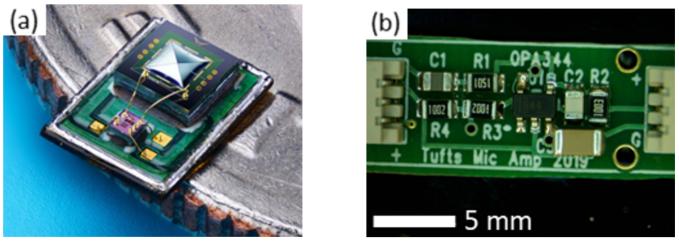

Fig. 1.(a) Vesper VM1000 MEMS microphone (lid removed) showing MEMS die and integrated preamplifier (3.76 mm × 2.95 mm ×1.1 mm). (b) photograph of one of the second stage amplifier boards.

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small size. These sensors have been designed for room temperature operation in air, but in the HTS applications, the sensors will experience low vacuum during pump down, and then immersion into cryogenic coolants (low temperature gaseous, liquid nitrogen or liquid helium). Characterization of the sensors and amplifiers, and optimization towards operation inside cryogenic coolant are lacking.

With this motivation, a technique for calibrating MEMS sensors in low temperature helium gas was developed. In this work we demonstrate calibration of the Vesper VM1000 commercial MEMS piezoelectric microphone with integrated preamplifier and characterize two types of second stage amplifiers in helium gas. Amplifiers based on the LMH6629 BiCMOS SiGe op-amp dramatically outperform (by >55 dB) those based on the OPA344, a rail to rail CMOS operational amplifier (op-amp), at temperatures below 230 K. The MEMS microphone itself appears to perform acoustic measurements down to 165 K in the 100 Hz to 10 kHz band, but with some loss of sensitivity down to 60 K. However, this sensitivity change appears repeatable and measurable, and is not expected to be a serious impediment to implementation of the quench detection method.

II. Experimental Procedure

A. MEMS Microphone Sensor and Second Stage Amplifier

The Vesper VM1000 MEMS microphone, and the second stage amplifier are shown in Fig.1. When testing in air, it was found that without second stage amplification, the apparent self-noise of the MEMS microphone was 36 dB above the actual background acoustic noise. With a second stage amplifier the noise measured reduces to within 2 to 5 dB of the true acoustic background level in an anechoic chamber, as measured by a Rion sound pressure level meter (37 dBA). This is the motivation for using a second stage amplifier. Two versions of second stage amplifiers, using the same circuit but different components, were tested. A circuit diagram and the components of the circuit are given in Fig. 2. The first design utilized the OPA344, a rail to rail CMOS operational amplifier specified for operation above 233 K according to the manufacturer [20]. The second design used the LMH6629 BiCMOS SiGe device which is intended for radio frequency and photonic applications. It utilizes C0G/NP0 or X7R capacitors and Susumu 0.05%,10 ppm/°C resistors. This amplifier has previously been used successfully in cryogenic environments down to 4.3 K [21]–[23].

B. Acoustic Testing in Helium Gas

Low temperature testing was conducted in a 0.076 m diameter, 1.11 m deep cylindrical two stage Gifford-McMahon cryocooler. The experiment setup is shown in Fig. 3. The helium gas pressure was maintained between 1.25 to 1.35 bar throughout the measurements using a pressure regulator. The acoustic test probe is an open-end square fiberglass tube with inner dimension of 19 mm and outer dimension of 25 mm. An electrodynamic speaker is mounted to the top of the test assembly, sealing the top of the tube against the speaker face. The

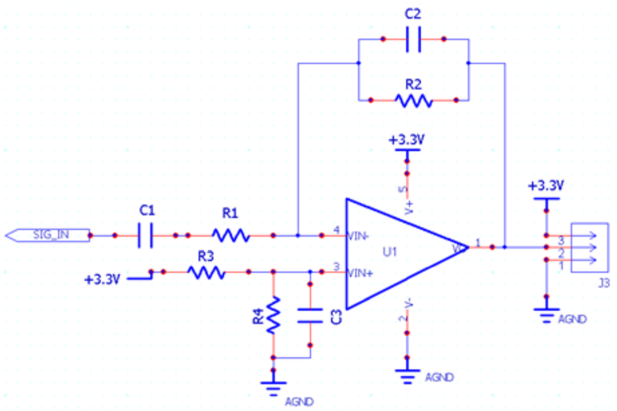

Fig. 2: Second stage inverting amplifier circuit. For OPA344, R_1=1.5 kΩ, R_2=100 kΩ, R_3=R_4=1 kΩ, C_1=4.7 µF, C_2=100 pF, C_3=1 µF. For LMH6629, R_1=470 Ω, R_2=5.1 kΩ, R_3=R_4=1 kΩ, C_1=10 µF, C_2=1 nF, C_3=1 µF.

temperature of the speaker stays above 280 K to ensure normal operation. Two MEMS microphones are mounted on the outside of the square tube with small diameter acoustic ports drilled through into the interior as shown. A Cernox 4-wire resistance temperature detectors (RTDs) and the second stage amplifier is mounted at the location of each of the MEMS microphones. The temperature of the top MEMS sensor remains above 230 K throughout the run, and can serve as a reference sensor, while the temperature of the bottom sensor drops as low as 60 K in these experiments. Frequency response data is gathered over a frequency band from 100 Hz to 10 kHz.

The speaker transfer function, tube acoustics, and microphone are all impacted by the temperature, pressure, and type of gas. The amplifiers are only impacted by the temperature.

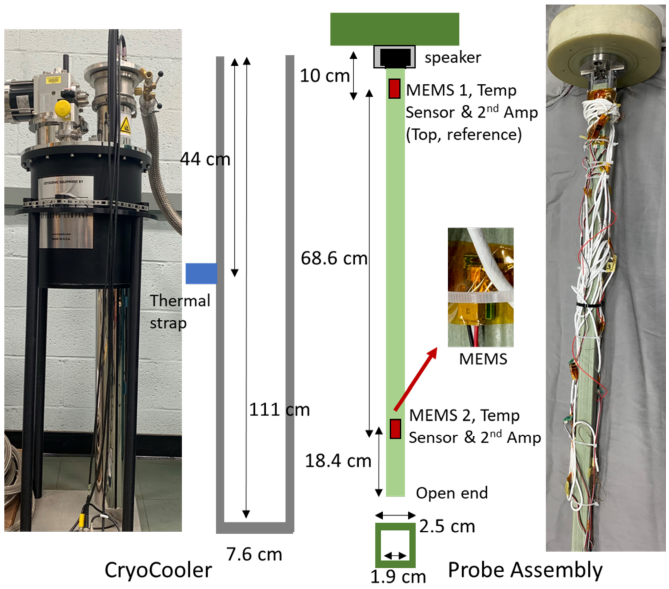

Fig. 3. Diagram and photograph of the CryoCooler and Probe Assembly.

III. Results and Discussions

The amplifiers were first calibrated without the microphone. Representative frequency response curves are shown in Fig. 4 for the two amplifier designs measured at 295 K and 60 K. The

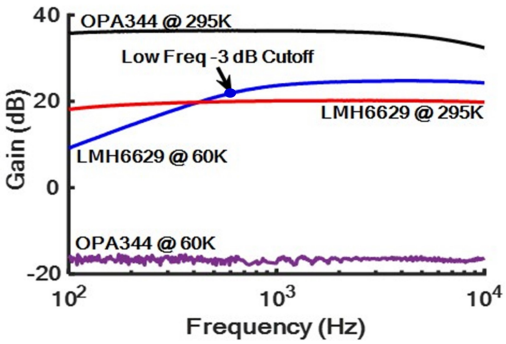

Fig. 4: Frequency response measurements of the second stage amplifier (without microphone) at 295 K and 60 K using the LMH6629 and OPA344 ICs.

difference in gain between the two designs at room temperature was set using the resistor values to achieve amplifier stability. At low temperatures, the OPA344 circuit gain drops by 55 dB. The LMH6629, on the other hand, maintains a passband gain within 5 dB of the room temperature gain across the full temperature range. However, the low frequency -3 dB cutoff increases at lower temperatures indicating the amplifier is less sensitive to low frequencies. The deviation of the mid-band gain from that at 295 K, and low frequency cutoff frequency, are plotted against temperature in Fig 5. In this plot the measurement has been repeated 3 times for the LMH6629 and twice for the OPA344. The LMH6629 base amplifier substantially outperforms the OPA344 at temperatures below 230 K.

During acoustic testing of the microphones, a frequency response of each of the microphones is measured using a swept-sine technique at a series of temperatures. In order to evaluate the expected acoustic pressure at the measurement location, an acoustic model of the helium-filled plane wave tube was employed. A temperature gradient exists in the cryocooler along the length of the plane wave tube. The temperature profile was first characterized using RTDs, and then the acoustic properties (speed of sound, density, viscosity, and thermal conductivity) of the helium gas were computed as a function of position down the tube using the ideal gas results for sound speed and density at the measured static pressure, and fitted results from [24], [25]

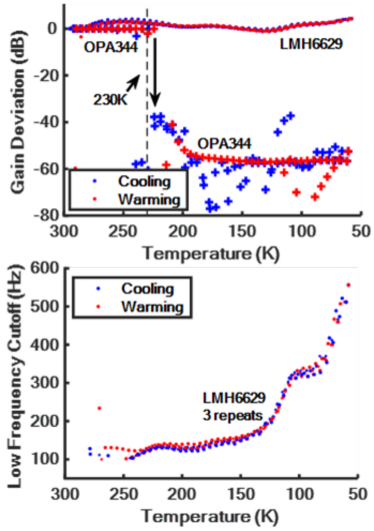

Fig. 5: Low frequency sensitivity of LMH6629-based circuit at low temperatures. At 60 K, the -3 dB cutoff has moved up to 500 Hz and increases monotonically with decreasing temperature.

for viscosity and thermal conductivity. The heat capacity of helium is a weak function of temperature above 10 K and is presumed constant. With these properties in hand, the classical acoustic absorption coefficient and the absorption coefficient for losses in a wide pipe were determined using the standard expressions [26]. Wide pipe losses are appropriate as the viscous boundary layer thickness over the range of values seen in these experiments never exceeds 0.6 mm and the pipe diameter is 19 mm. The solution to the acoustic field in the tube comes from solving the acoustic wave equation with a position dependent sound speed and absorption using the Wentzel-Kramers-Brillouin (WKB) technique [26]. The solution for pressure is

$$p(x,t) = \left[Ae^{-j\left(\int k(x)dx\right)} + Be^{j\left(\int k(x)dx\right)} \right] U(x) e^{j\omega t} \quad (1)$$

where the variation of the acoustic properties with distance down the tube, x, results in a position dependent wavenumber, $k(x)$, that is the solution to the eikonal equation,

$$k(x) = \frac{\omega}{c(x)} - j\alpha(x) \quad (2)$$

$k(x)$ depends on circular frequency, ω, the local speed of sound, $c(x)$, and the local absorption, which includes both classical and wide pipe absorption, $\alpha(x) = \alpha_c(x) + \alpha_w(x)$. In order to conserve energy, the transport equation requires that the envelope function, $U(x)$, be

$$U(x) = \sqrt{\rho(x)c(x)} \quad (3)$$

where $\rho(x)$ is the local helium density. The boundary conditions at the ends of the tube are the velocity imparted by the acoustic driver, determined from driver input electrical impedance measurements in helium, and the well-known unflanged acoustic termination impedance for a square pipe. Application of the boundary conditions allows determination of the amplitude of the backward and forward waves, A and B. The result can then be plotted against frequency at the location of the MEMS microphone and compared to measurement, using the manufacture provided microphone sensitivity, as shown in Fig. 6. The model does a good job predicting the frequencies of the maxima and minima seen in the frequency response, and also the levels of

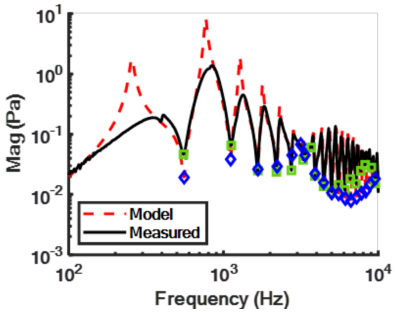

Fig. 6: Comparison of the predicted and measured pressure at the upper microphone location for helium at 1.23 bar and 293 K. Measurements are with VM1000 microphones and using the OPA344 amplifier. To avoid sensitivity to resonance, the two curves were compared in the valley regions (minima) between resonant peaks, as indicated by square (from measurement) and diamond (from model).

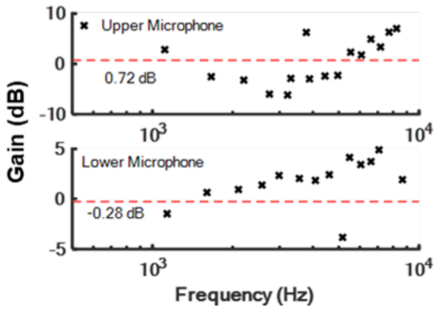

Fig. 7: The ratio of the measured and expected pressure at the minima in the frequency response, in helium at 1.23 bar and 293 K for microphones in the two locations. The top plot is the same data as Fig. 6.

the minima. The absolute levels of the maxima are difficult to predict due to their sensitivity to the accuracy of the absorption model. In order to compare the microphone response to theory, it is best to compare the levels at minima, or the valley region between resonant peaks, to avoid sensitivity to resonance. The minima are indicated by the squares (from measurement) and diamonds (from model) in Fig. 6. Subtracting the measured and modeled dB levels at the minima gives deviation from theory, as shown in Fig. 7 for two microphones, at 293 K. The result demonstrates agreement with the manufacturer provided sensitivities within ± 7 dB across the mid-band from 500 Hz to 5 kHz for both microphones. The average deviation in that band is 0.72 dB for the top microphone and -0.28 dB for the bottom microphone, an encouraging result.

Finally, this method is applied at each temperature during a temperature run down to 60 K and back up to 290 K. The resulting average gain across the 500 to 5000 Hz band is plotted in Fig. 8 for the top and bottom microphones using both the OPA344 and LMH6629 amplifier boards. The top panel of the figure shows the upper microphone, which never experiences a temperature below 230 K. This microphone always maintains a sensitivity within 5 dB of manufacturer sensitivity. The middle panel shows two different microphones at the lower position, each measurement repeated twice, using the LMH6629 board. At temperatures above 165 K, the microphones show sensitivities within 20 dB of the room temperature sensitivity. Little hysteresis is seen in the response, and the microphone output is very similar during warming and cooling. One of the microphones shows a repeatable response in the two tests at temperature above 165 K. The other shows a different response in the

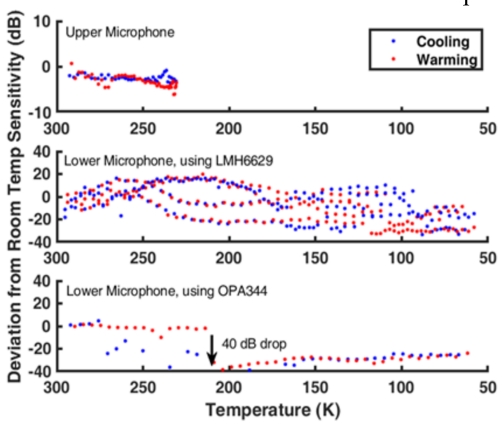

Fig. 8: The mean measured acoustic pressure output of VM1000 microphones using either the LMH6629 or OPA344 amplifier over the 500 Hz to 5 kHz band during swept sine measurements, as compared to manufacturer supplied sensitivities. Measurements are in helium at pressures between 1.23 and 1.35 bar, and temperatures from 300K down to 60K.

second run than the first run. The cause of this lack of repeatability for one of the microphones needs further investigation. Regardless, the two microphones do appear to provide acoustic response using the manufacturer's co-packaged ASIC preamplifier, down to 165 K. Below 165 K the response becomes less repeatable and exhibits hysteresis. For some of the tests, the output reduces to the noise floor of the measurement (-30 dB). At this stage of investigation, it appears that the Vesper microphone with the manufacturer's ASIC preamplifier can operate successfully down to 165 K, but it is not yet clear if the system is still functional acoustically below that temperature. The bottom panel shows a single result using the OPA344 electronics. As expected, this system suddenly drops in gain by 40 dB as temperatures drop below 230 K. This is presumably due to the inability of the OPA344 to operate below 230 K as shown in Fig. 4 and 5. In all results we see the microphones and amplifiers returning to normal operation when temperatures return to near 300 K.

IV. Conclusion

To develop an acoustic quench detection method using MEMS acoustic sensors, commercially available MEMS microphones and op-amp based audio amplifiers were characterized under cryogenic conditions. A method was developed to investigate acoustic performance in helium gas from room temperature down to 60 K at static pressures between 1.20 and 1.35 bar. To reduce the signal to noise ratio of the microphone, two types of second stage audio amplifiers, based on the OPA344 and LMH6629 operational amplifiers, were tested. The OPA344 fails below 230 K, while the LMH6629 second stage amplifier operates down to 60 K with no loss of passband gain, although some loss of low frequency bandwidth is observed. Acoustic testing demonstrates that VM1000 piezoelectric MEMS microphones are able to perform acoustic measurements in gaseous coolant down to cryogenic temperature, with no permanent damage. However, more investigation on hysteresis, possible loss of signal, and repeatability are need at temperatures below 165 K. The calibration method developed allows testing of various types of MEMS sensors as candidates in the future. Initial results show promise, but to implement this proposed acoustic quench detection method, more work is needed on MEMS sensor acoustic characterization in cryogenic coolants, as well as more information on the frequency range and dynamic range of quench event acoustic pressures.

Future work will further investigate the source of sensitivity variations at low temperatures. In addition, an acoustic calibration method in liquid cryogenic coolants will be developed. Finally, experiments of HTS-CICC using those custom designed MEMS sensors will be accomplished to verify the efficacy on this methodology in a real-life scenario.

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