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Characterization of a Low Frequency Magnetic Noise from a Two Stage Pulse Tube Cryocooler

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Magnetic noise of a two stage pulse tube cryocooler(PT) has been measured by a fundamental mode orthogonal fluxgate magnetometer and by a LTS SQUID gradiometer. The magnetometer was installed in a Dewar made of aluminum at 12 cm apart from a section containing magnetic regenerative materials of the PT. The magnetic noise shows a clear peak at 1.8 Hz which is the fundamental frequency of the He gas pumping rate. The 1.8 Hz magnetic noise took a peak, during the cooling process, when the cold stage temperature was at (or close to) 12 K, which resembles the variation of the temperature of the second cold stage of 1.8 Hz. Hence we attributed the main source of this magnetic noise to the temperature dependency of magnetic susceptibility of magnetic regenerative materials such as Er3Ni and HoCu2 used at the second stage. We pointed out that the superconducting magnetic shield by lead sheets reduced the interfering magnetic noise generated from this part. With this scheme, the magnetic noise amplitude measured with the first order gradiometer DROS, mounted in the vicinity of the magnetic regenerator, when the noise amplitude is minimum, which could be found from the fluxgate measurement results, was less than 500 pT peak to peak. Whereas without lead shielding the noise level was higher than the dynamic range of SQUID instrumentations which is around ±10nT.

Key words: *Pulse tube, Magnetic measurements, Magnetic shielding, Regenerators, SQUIDs*

1. Introduction

Superconducting quantum interference devices (SQUIDs) have been used to measure magnetocardiogram (MCG) and magnetoencephalogram (MEG) fields to diagnose heart diseases and brain functions. One of the prerequisites for operation of SQUIDs is the low temperature sources that usually obtained with liquid helium. Closed cycle cryocoolers are a potential low temperature source for SQUID systems. If use of such cryocoolers for cooling SQUIDs becomes possible the operation costs such as liquid helium handling charges will be eliminated. The most critical parameter for using such systems for cooling SQUIDs is the influence of the cooler noise on the operation of the SQUID system.

Existence of low frequency magnetic noise in cryocooler based SQUID systems has been reported by several authors. For example low frequency noise of a Gifford–McMahon cryocooler (GM) has been measured by a drung type magnetometer[1)]. Construction of a MEG measurement system by integrating LTS SQUID with GMJT cryocooler has been reported.[2-3)] Qualitative analysis of the cyclic noise based on the measurement of the noise of a GM at various times (and therefore various temperatures) by using a 32 channel cryocooled system has also been reported. The source of the magnetic noise has been attributed to the presence of austenitic stainless steel because of similarity between noise temperature dependency and the austenitic stainless steel magnetic property temperature dependency. But in this case they have not presented any quantitative data about these dependencies. An interference characterization on a JT has been performed in Ref. [4)], but in this research also there is not any analysis on magnetic noise generated by cryocooler itself. In another research [5)] the noise generated by a GM has been measured by a fluxgate type magnetometer in two different configurations, in one configuration the second displacer has been filled with lead spheres and in the other it

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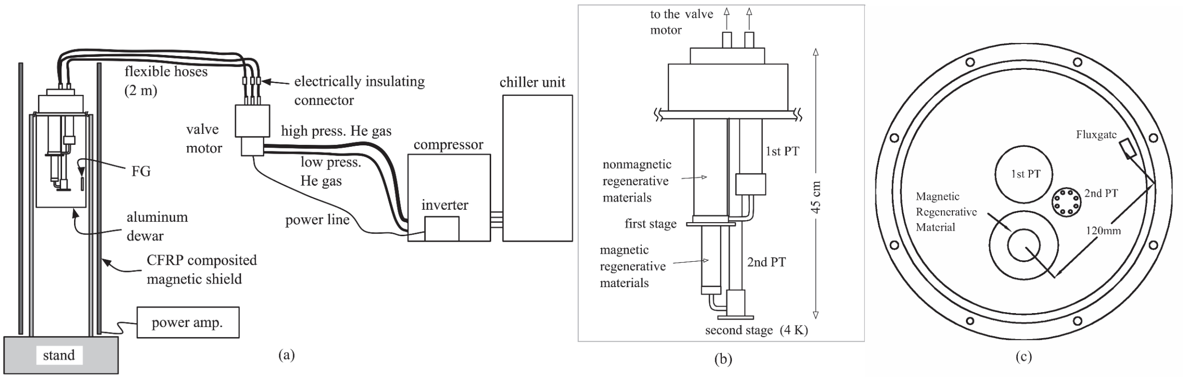

Fig.1 (a) Experimental setup including CFRP shield, compressor and valve motor. (b) Structure of two stage pulse tube cryocooler (c) Cross section of the cryostat and relative location of the fluxgate with respect to the magnetic regenerative part.

has been filled with Er3Ni. This comparison shows that displacer filled with Er3Ni will result in about one order increase in magnetic noise. Although the minimum obtainable temperature with lead filled displacer is above 8 K, but this observation supports the idea that the magnetic regenerative materials are one of the sources of the low frequency magnetic noise. From the pattern of magnetic noise, measured with LTS SQUID cooled by GM, the authors concluded that the elements producing the unexpected magnetic noise are thought to be in the displacer.

As to our knowledge there is no quantitative characterization study on the magnetic noise generated by the two stage PT for cooling LTS SQUIDs and also the noise source or sources are still unidentified. Therefore characterizing the noise of such systems and finding the noise source location and also evaluating the interference of the noise on LTS SQUID operation and a relatively simple method to reduce the magnetic noise are of great importance. Among the several types of available cryocoolers the PT is more stable than the other types such as GM [6], with regard to physical vibrations and also magnetic field noise due to the magnetic regenerative material movements, because it has no moving part in the cold stage.

For treating the noise of such systems in a systematic approach, its location should be identified. One way for finding the noise location is the study of its behavior and its dependencies to the operating parameters such as cooling stages temperatures. If the noise source location of such system well identified, finding methods to reducing the noise influence on SQUID operation will be straightforward. In this investigation we characterized the low frequency magnetic noise of a PT, which is present whenever cryocooler is operating. Analyzing the time evolution of level of this magnetic noise and temperatures of the cooling stages suggests that the magnetic noise source could be the magnetic regenerative part. In PT magnetic regenerative materials such as Er3Ni and HoCu2 are used in the 2nd stage regenerator [7], because of their large heat capacity at temperatures below 15 K. These materials (Er3Ni and HoCu2) show a paramagnetic to antiferromagnetic phase transition around 10 K and 7 K respectively, and this phase transition is responsible for their large heat capacity at low temperatures. The excursion of helium gas in pulse tube and regenerative material will change the temperature of the regenerative material with a periodical manner, so the magnetic susceptibility of regenerator will be changed accordingly. The temperature dependency of magnetic susceptibility of regenerator could be a source of the low frequency magnetic noise in the existence of the background magnetic field. Finally by use of lead sheet as a superconducting shield over the magnetic part the level of magnetic noise has been reduced down to 90% of its initial level.

2. Experimental Setup

With a fundamental mode orthogonal fluxgate magnetometer [8] that works over a wide temperature range we measured the time varying component of the magnetic noise during the cool down process. By adding a calibration coil to the fluxgate, we confirmed its sensitivity each time upon measurement and that the measured magnetic noise variation is just because of the field change. The cryocooler used in this measurement is a special model, in which the cryostat and the valve motor are separated by about 2 meters. Three flexible tubes made of thin stainless steel are connected to the valve motor via electrically insulated connectors to reduce the conductive electromagnetic noise generated by a compressor and a valve motor. The cryostat was set in a cylindrical magnetic shield developed in our laboratory whose transverse shielding factor (TSF) for a low-frequency time-varying magnetic field is as large as 40,000 when magnetic shaking enhancement is on, whereas 140 along its axis [9].

Compressor pressurizes the helium gas up to 2 MPa and supplies it to the PT at the 1.8 Hz frequency with the rotation of the valve motor. The fundamental mode orthogonal fluxgate is fixed to the inner wall of vacuum chamber of cryostat in vertical direction 12 cm apart from magnetic regenerative part. The cryostat has been set up near the center of the CFRP cylindrical shield (Fig.1 (a)). Fig.1 (b) shows the structure of the two stage PT used in this investigation. Relative position of the fluxgate with respect to the regenerative part has been demonstrated in the Fig.1(c). The temperature of the second stage was measured with a germanium thermometer. The germanium sensor was attached to the SQUID copper holder with indium sheets to facilitate the thermal conduction. The temperature indicator instrument is a lakeshore 234D model which has an analog output. We measured the amplitude of the 1.8 Hz component of the magnetic noise and the 2nd stage temperature variation with the aid of two channel FFT analyzer model SR780. All the data from temperature indicators and Lock In Amplifier and FFT analyzer has been acquired automatically with National instrument DAQ board and serial communication with FFT analyzer and Labview Software.

3. Measurement Result and Discussion

Fig.2(a) shows FFT spectrum of the fluxgate magnetometer which was measured when 2nd stage temperature was at 7.8 K and cryocooler was off. Fig.2(b) shows the FFT of the output of the temperature measurement system at 14 K when cryocooler is operating. The temperature variation shows a clear peak at 1.8 Hz. The peak at 2 Hz in this graph is related to the temperature measurement system and is present at temperatures below 60 K even if the cryocooler doesn't operating. The magnetic noise spectrum when 2nd stage temperature was at 11 and 43 K are shown in Fig.3. Peaks are clearly visible in these two graphs at 1.8 Hz. It is also visible that the peak becomes larger at 11 K. The higher harmonics of 1.8 Hz is also visible in these graphs. For analyzing the 1.8 Hz magnetic noise time dependence (hence temperature dependence), the amplitude of these peaks has been sampled from FFT spectrum every 16 seconds. The 1.8 Hz component in magnetic field spectrum always existed while the PT was operating. During the cool down process, 1.8 Hz component of magnetic noise has an almost fixed constant value down to reaching 22 K. After this point it shows a rapid increase and after reaching a maximum around 12 K (Fig.4(a)) it tends to reduce. The background magnetic field has a variable value in the range of ±1500 nT during the cool down process. This variation could be because of the change in the susceptibility of the magnetic parts due to the temperature change.

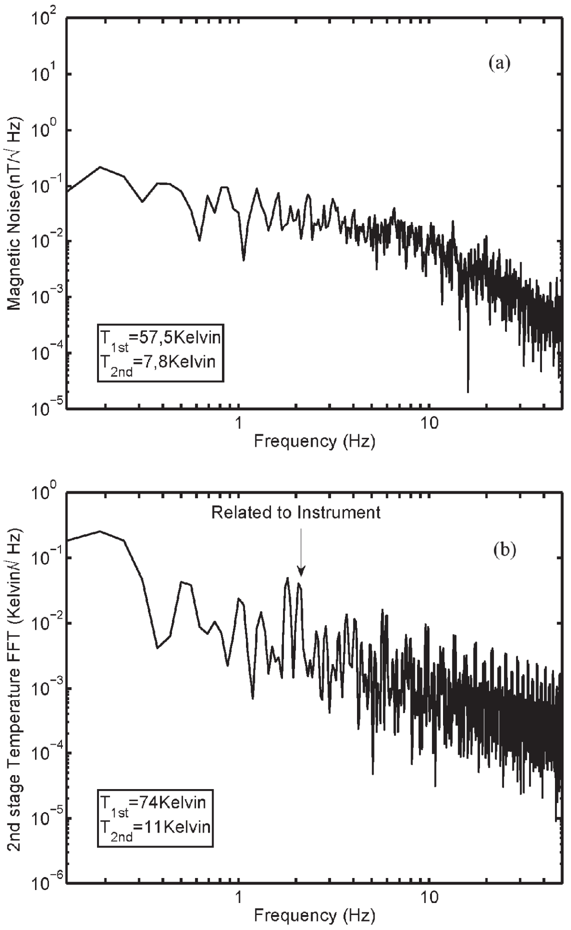

Fig.2 (a) FFT spectrum of the magnetic field measured at 7.8 K when cryocooler is off. (b) FFT of analog output of temperature measurement system captured at 11 K. The 2 Hz component shown by an arrow in the figure is related to temperature measurement system itself not to temperature variation.

We found out that the plot of 1.8 Hz compo-

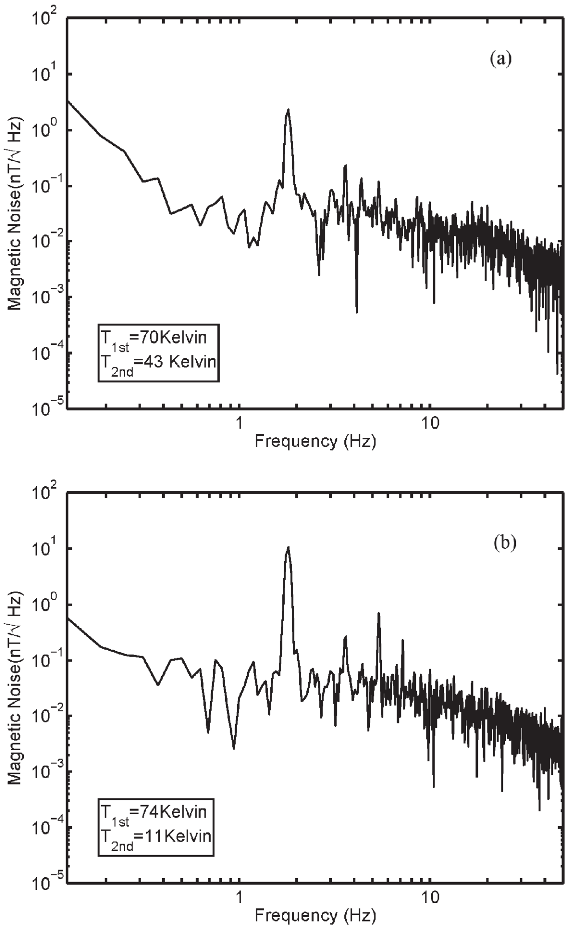

Fig.3 Magnetic noise spectrum measured by Fluxgate magnetometer (a) $T_{2nd} = 43K$ (b) $T_{2nd} = 11K$

nent of magnetic noise and 1.8 Hz component of temperature variation during the cool down process, resemble each other (Fig.4(a)). The volumetric specific heat of the ^{4}He working fluid at temperature range of 5 to 15 K is large, in comparison to that of the low temperature regenerative materials, and peaks around 10 K [10], So magnetic regenerative materials will undergo large temperature variation when helium gas within this temperature range pass through them and will produce larger magnetic noise because of undergoing larger temperature variation. After the 2nd stage cold head reaches its lowest temperature, the first stage temperature sharply start to fall. This phenomenon could help us to reveal the effect of change of just one parameter (first stage temperature), while the 2nd stage temperature is maintained at its lowest value, on the magnetic noise. Finding the magnetic noise dependency on just one parameter could be helpful for finding the noise source. In this part of the cool down process, the warm end of the 2nd stage regenerator is maintained at 1st stage temperature, so temperature reduction of the first stage will decrease the temperature gradient in 2nd stage regenerative part, hence there will be larger volume at cold temperatures. The magnetic susceptibility of Er3Ni and HoCu2 have a maximum around 12 and 10 K respectively [11]. Therefore reducing the first stage temperature will increase the mass of the magnetic material at temperatures between 10 and 12 K and consequently will increase the magnetic noise amplitude.

The magnetic noise amplitude has a minimum value around 22 K. Probably at this moment whole the magnetic regenerative part is at almost same temperature and hence the change in temperature is small. The 2nd stage regenerative part of our cryocooler consists of Lead at the warmer end followed by Er3Ni and HoCu2 toward colder end. The lead heat ca-

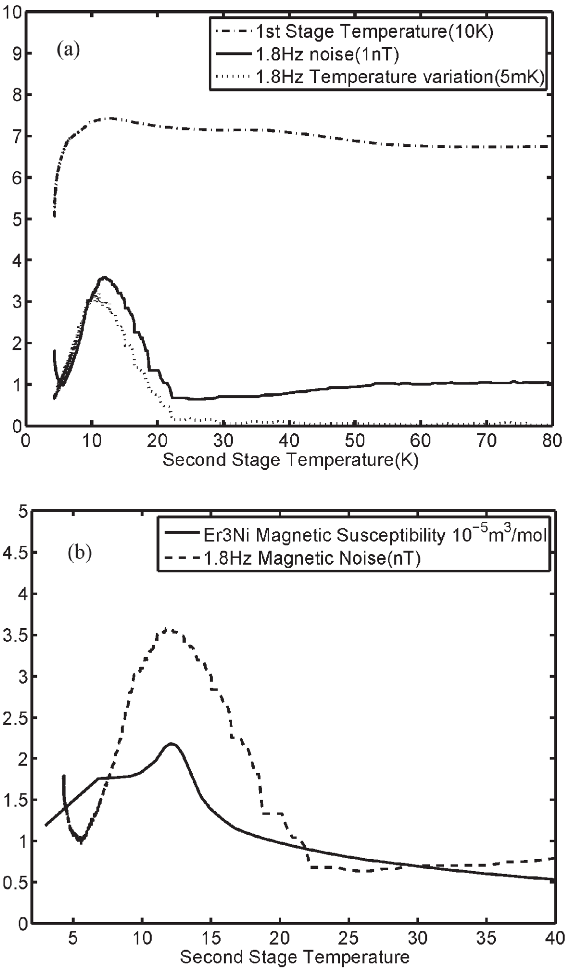

Fig.4 (a) Temperature dependency of 1.8 Hz magnetic noise (Continuous line) and 1.8 Hz variation of 2nd stage temperature (dotted line) resemble eachother. (b) Temperature dependency of Magnetic susceptibility of Er3Ni ($10^{-5}m^3/mol$)[11], 1.8 Hz component of magnetic noise(nT).

pacity at temperatures higher than 20 K is higher than that of two other materials. So probably when the 2nd stage cold head is at 22 K, the major temperature gradient in the 2nd stage regenerator is just through the lead part of the 2nd stage regenerator and whole the magnetic part is fixed at almost same temperature, so the magnetic materials undergo very small temperature variation and produce very small magnetic noise. The magnetic noise produced by magnetic regenerative material could be formulated as the following relationship:

$$H_{1.8} = \alpha \sum \partial\chi\left(T\left(x\right)\right) / \partial T \square \Delta T_{1.8}(x) \square H_{background}$$

While x is the distance from the cold end in 2nd stage regenerator and α is a proper proportional coefficient. The presence of magnetic noise at the temperature range in which the susceptibility of magnetic regenerative materials is small (Fig.4a), suggests that there is two source for magnetic noise. The other source could be presence of materials such as stainless steel in the Dewar which are used for making pulse tubes and regenerator tubes. The vibration of such materials due to the helium gas excursion could generate temperature independent magnetic noise.

4. Measurement of Magnetic Noise by the First Order Gradiometer SQUID

DROS type first order gradiometer[13] has been mounted on a copper stage which is attached directly on the cold head of the PT in vertical direction in the same elevation with magnetic regenerator part and just about 7 cm horizontal separation from that. A Germanium temperature sensor is also attached to this copper stage. The aluminum vacuum chamber has been replaced by FRP one to reduce the thermal magnetic noise. For operating DROS inside the cryostat the interfered high frequency noise conducted through flexible hoses from an inverter driving a valve motor to the cryostat should be reduced. For this purpose we monitored the high frequency current paths to the valve motor and found that there is a large unbalanced current in the flexible hoses and power lines, therefore we tried to reduce the impedance of the neutral line by covering it with copper mesh jacket to force the some part of the unbalanced current to flow into the neutral line and to reduce the amount of the conducted noise current to the cryostat. The detailed scheme that we used for reducing this high frequency noise is described elsewhere [14].

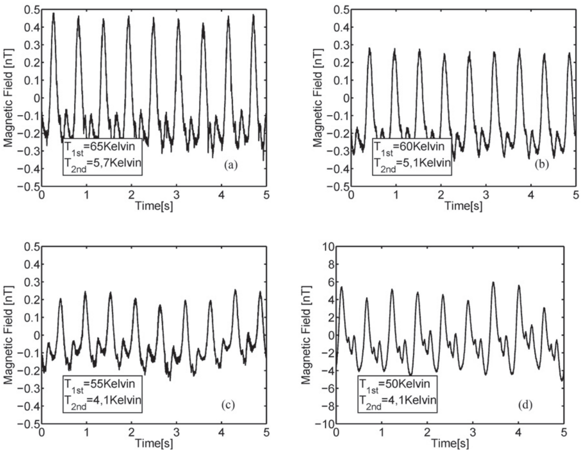

Fig.5 Magnetic noise gradient waveform measured by first order gradiometer DROS during cool down process at various temperatures. The frequency of peaks is 1.8 Hz. The figure(c) corresponds to the minimum noise level in Fig. 4. Figure(d) shows increase in noise level due to the increase in volume of magnetic material as a result of 1st stage temperature fall down.

After employing the aforementioned scheme the DROS has been operated successfully in the cryostat, but we observed that the 1.8 Hz magnetic noise amplitude is larger than the dynamic range of our SQUID system which is about ±10 nT. For suppressing this low frequency noise we used the shielding effect of superconducting lead sheet. In this case use of any high permeability material such as amorphous materials over the regenerative part is not efficient, because these materials will enhance the background magnetic field and also produce some extra magnetic noise due to vibration. For cooling the lead sheet to put it to the superconducting state we used several copper foils connected to the cold head of the cryocooler at one end ,with indium sheet in between to facilitate thermal conduction, and wrapped the other end around the $100\mu m$ thick lead sheet which is wrapped on the 2nd stage regenerative part. With this scheme we measured the magnetic noise with first order gradiometer DROS type SQUID at several different times (and hence different temperatures) and confirm the noise behavior when 2nd stage temperature is below 6 K. Fig. 5(a) and (b) show the noise waveforms before reaching the minimum noise level. The measured magnetic noise with DROS when the 1.8 Hz magnetic noise has its minimum value around the time that the 2nd stage temperature reaches its lowest value and 1st stage temperature doesn't start to reduce was less than 500pT (Fig.5(c)). The sharp increase in noise amplitude from less than 500 pT at the minimum point to more than 8 nT after reaching 1st stage temperature to 50 K is not apparent in fluxgate measurement result (Fig. 4). This could be because of difference between measurement methods, our fluxgate is a magnetometer while The DROS is a gradiometer. The other probable reason could be the unshielded noise sources present in cryostat such as stainless steel tubes. In addition due to the limited size of superconductor shield, excess drop of first stage temperature will extend the cold magnetic regenerator to the ends of the superconductor shield and causes more interference. It should be noted that in this measurement SQUID has been positioned parallel to and at the same elevation with regenerative part and just about 7 cm horizontal separation from that. In our next step in addition to superconducting shielding, we will increase the vertical separation between SQUID and regenerative part. We also hope that by adjustment of the 1st stage orifice we could lift the first stage temperature to its optimum level which permits the 2nd stage be at 4.2 K and magnetic noise be at its minimum level for long time operation. In this condition the shielding factor of lead shield is over 40. Fig.5 shows a typical output waveform of the SQUID measurement when the cooler noise is minimum.

5. Summary and Conclusion

Magnetic noise of a two stage pulse tube cryocooler has been characterized with the fundamental mode orthogonal fluxgate magnetometer. We observed that the amplitude of 1.8 Hz magnetic noise is dependent on the 1st and 2nd stage temperatures. When the 2nd stage cold head is at 4.2 K, the 1st stage temperature is the governing parameter. As long as the second stage temperature is kept at 4.2 K, decreasing the first stage temperature will increase the 1.8 Hz magnetic noise amplitude and vise versa. Therefore by lifting the 1st stage temperature as high as possible, while keeping the 2nd stage temperature at 4.2 K, the amplitude of this noise can be made minimum.

With the aid of superconducting shielding over the magnetic regenerative material we measured the magnetic noise with DROS mounted on 2nd stage cold head. Based on the noise amplitude measured by DROS when the magnetic noise reaches its minimum value the shielding factor of superconductor shielding made of lead sheets is larger than 40. The magnetic noise amplitude measured with first order gradiometer DROS type SQUID at this condition at 7 cm horizontal separation from regenerative part was less than 500pT. In our next step we will attach the SQUID in a further position with respect to the regenerative part to achieve less low frequency noise.

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