Low Temperature Characterization of Mechanical Isolators for Cryocoolers

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ABSTRACT

For spacecraft applications requiring active refrigeration, exported vibrations from a cryocooler can be a concern. One approach to minimizing the vibrations transmitted from cryocoolers to the spacecraft is to mount them on mechanical isolators. Many commercial off-the-shelf (COTS) mechanical isolators exist and have been characterized at room temperature for ground applications. However, the space environment presents challenges that complicate the selection process. For example, mechanical isolators in space must be made of materials that can withstand harsh thermal and radiation environments. Future instruments, such as the Mapping Imaging Spectrometer for Europa (MISE) on the Europa Clipper mission, are considering operating cryocoolers with low heat rejection temperatures and mounting them on mechanical isolators. However, the performance of many simple, traditional mechanical isolators at low temperatures is unknown. This paper describes the testing and results of various mechanical isolators able to withstand harsh radiation between 200 K and 300 K. Fluorosilicone rubber sheets showed very little isolation even at room temperature. The transmissibility of silicone gel was strongly dependent on temperature and had a drastic change in behavior between 220 K and 240 K. On the other hand, the transmissibility of wire rope type isolators showed very little temperature dependence. In addition, custom titanium flexures are promising because they can be designed to specifications easily.

INTRODUCTION

Vibration isolation of mechanical cryocoolers from spacecraft may be required to mitigate the disturbances imparted on delicate science measurements elsewhere onboard. Vibration suppression can be achieved with active methods and/or isolation can be achieved with passive methods. Active methods are complex and require feedback control. For opposing piston compressors with large piston axis disturbances, the input voltage signal to one motor can be modified so that the disturbance in that axis is minimized. Low-cost, flight-qualified cryocooler electronics made by Iris Technologies® have this feature built-in and it has been demonstrated to be effective [1]. However, this method does not minimize disturbances in the radial piston directions. Active mass dampers can be implemented in these axes, further increasing complexity. On the other hand, passive isolation is attractive for its simplicity. Typically, the isolated component is attached to its base structure by means of robust isolating mounts, which have low relative stiffness [2]. The natural frequency of the mount is selected in order to provide isolation in the frequency range of choice that is driven by the cryocooler drive frequency. An energy-dissipating and load-supporting material such as a...
natural or synthetic rubber may be sufficient for most applications [3]. However, in general, the Young’s modulus and shear modulus of these materials are dependent on temperature, thus they may not perform well in cold environments [4]. Finally, the potential large relative displacements between the cryocooler and mounting structure during spacecraft launch must be considered. Approaches to accommodating launch loads include designing isolators capable of surviving launch [5] or building bumpers to limit displacement [6].

The Europa Clipper will orbit Jupiter and image its icy moon during its 45 planned flybys. All materials on the spacecraft must be able to withstand large radiation doses from Jupiter. For example, the MISE cryocooler will see a total ionizing dose of 250 krad and it is contained in a one centimeter thick aluminum radiation shield [7]. Furthermore, all materials must perform at cold operating temperatures. Rubbers and soft plastics are not robust enough to endure this environment, thus new materials need to be explored. The MISE Instrument plans to operate a Lockheed Martin Micro1-2 cryocooler in a 220 K environment [7]. This cryocooler will operate at 135 Hz and the exported cryocooler vibrations in the compressor radial direction are on the order of one Newton measured zero-to-peak [1]. The goal of this study is to identify potential candidate isolators that would (i) mitigate disturbances from the MISE cryocooler, (ii) survive the Europa radiation levels, and (iii) perform appropriately at 220 K.

This paper details the methods and results of testing of four types of isolators that are impervious to radiation, namely fluorosilicone rubber, silicone gel, stainless steel wire rope, and titanium flexures. They are shown in Figure 1 and described in Table 1. Two different sizes of Advanced Antivibration Components® silicone gel isolators and two different IIT Enidine® wire rope isolators of different size and stiffness were tested at temperatures ranging from 205 K to 295 K. Three thicknesses of fluorosilicone rubber along with custom made titanium flexures were tested at room ambient conditions.

**METHODS**

The fluorosilicone rubber, silicone, and wire rope isolators were tested in a vacuum chamber. Figure 2a shows a schematic of the test setup and Figure 2b shows a photograph of the test setup used to test the silicone and wire rope isolators. A Labworks® shaker, excited in the vertical direction by a sine wave output from a Chroma® programmable AC source, was attached to a baseplate through a PCB® 208B force sensor. The baseplate was suspended from four elastic cables allowing large vertical accelerations in the baseplate resulting from the shaker input. Three G10 standoffs mounted to the baseplate supported the bottom of three isolators, which supported a 1.079 kg copper puck at their top. Three single-axis Kistler® accelerometers measured accelerations in all three axes on the baseplate and a Kistler® cryogenic accelerometer was aligned with the vertical axis on the copper puck. A black-painted copper shield was attached to the second stage of a CTI Cryogenics Cryodyne® 1050C cryocooler and cooled the puck and isolators by radiative heat transfer. The G10 standoffs served as thermal isolation between the cold copper puck and the warmer shaker baseplate.

![Figure 1.](image-url) (a) Fluorosilicone rubber sheets, (b) silicone gel isolator, (c) stainless steel wire rope, (d) titanium flexures.
The temperature reported in this manuscript corresponds to that measured on the copper puck, which was approximately the same temperature as the top of the isolators.

The isolators were cooled by radiative heat transfer for approximately 48 hours to below 205 K. Once they were below 205 K, the CTI cryocooler was turned off and the temperatures of the isolators increased at a rate of 0.1 K/min. At specified temperature increments, a LabVIEW® program was initiated that collected accelerometer data and swept the frequency output of the shaker. The voltage output of the AC source was kept constant during each data collection, and the frequency was swept from 31.25 Hz to 1000 Hz at a rate of one octave per minute. The sampling rate was set to 2.5 kHz for all measurements.

A fast Fourier transform was applied to the measured time domain data of each accelerometer and force sensor, and then the transmissibility was computed. It was defined as the ratio of output acceleration to input acceleration in the frequency domain. For clarity, a moving average window of 2,500 samples was applied to the transmissibility and electric noise harmonics were filtered out. Data before and after filtering electrical noise were compared to ensure no real results were affected.

### RESULTS AND DISCUSSION

#### Fluorosilicone Rubber

Fluorosilicone rubber was identified as a candidate material that had acceptable radiation tolerance. The 250-krad dose seen by the cryocooler would have a minimal effect on the isolating properties of the material [8]. Transmissibility measurements were made on sheets of different thicknesses, namely 0.032”, 0.093”, and 0.250”. Figure 3a shows the test setup used. An aluminum plate...
was mounted to the top of the G10 standoffs and the fluorosilicone rubber sheets were sandwiched between the copper puck and the plate. Preliminary tests were performed at ambient temperature and pressure to determine the potential of the material. Figure 3b shows the transmissibility vs. frequency for each thickness. In general, the isolation increased with increasing sheet thickness. All of the different thicknesses demonstrated isolation above 500 Hz with the exception of the thinnest sheet between 800 Hz and 900 Hz. In fact, all three thicknesses showed a local peak in transmissibility around 850 Hz. Figure 3b indicates that this material shows excellent isolation above 900 Hz. Unfortunately, the frequency range and overall isolation of this material were not sufficient to warrant testing at cold temperatures.

Silicone Gel Isolators

Silicone gel is desirable for its transmissibility at low frequencies and ability to withstand up to seven Mrad of radiation [9]. Figure 4 shows the transmissibility as a function of frequency for various temperatures of two sizes of silicone gel isolators. Both isolators demonstrated similar trends as a function of temperature; the transmission of each isolator was large at low temperature, but decreased as the temperature increased. A transition from non-isolating to isolating behavior occurred between 220 K and 230 K as the material passed its melting temperature [9]. Indeed, Figure 5 shows the modulus of rigidity of silicone rubber as a function of temperature [9]. It shows that silicone undergoes a gel-solid phase change and “melts” beginning at approximately 215 K.

Figure 3. (a) Fluorosilicone rubber sheet under copper mass. (b) Transmissibility of three thicknesses of fluorosilicone rubber

Figure 4. Transmissibility of large (a) and small (b) silicone gel isolators
These data are consistent with the results of a differential scanning calorimetry (DSC) analysis by Ref. [10], which shows an “endothermic melting peak” in DSC beginning at 215 K. The material completes its transition near 240 K [10]. This process causes the material to transition from complexly rigid to flexible, hence the intermediate behavior in this temperature range.

At warmer temperatures, the isolating behavior of the silicone gel improves as it approaches a minimum transmissibility of 0.01 near 500 Hz. Similar to the fluorosilicone rubber, there is a local peak around 850 Hz. The isolators again reach their minimum transmissibility near 1000 Hz. At low temperature, the input is amplified making these isolators unpredictable near their melting temperature where they are effectively a solid. Overall, the performance of these isolators was highly temperature dependent around 220 K and thus temperature independent alternatives were explored.

**Wire Rope Isolators**

Wire rope isolators damp vibration through the rubbing and sliding friction between their multiple twisted stainless steel cables [11]. Vibrational energy is dissipated as heat as adjacent cables move relative to each other [11]. Two different types of wire rope isolators of different stiffness and size were tested at various temperatures to assess if their performance was dependent on temperature. Shown in Figure 6 is the transmissibility vs. frequency for the two different models of isolator. The isolators in Figure 6a and Figure 6b respectively exhibited peaks in transmissibility near 100 Hz and 75 Hz where input amplification of around ten times occurred. The isolators did not exhibit a strong temperature dependence at lower frequencies and the transmissibility was less than one for...
frequencies higher than the break frequency of 130 Hz and 100 Hz, respectively. These isolators showed promise being temperature independent, however their behavior is extremely challenging to model/predict. Neither of the wire rope isolators tested were capable of providing sufficient isolation for MISE due to their high break frequencies. MISE requires an order of magnitude force reduction at 135 Hz. Assuming a damped harmonic oscillator, a frequency separation of about 3.5 times the fundamental frequency is necessary to achieve this force reduction. Thus, the break frequency of the isolator needs to be less than 35 Hz.

Test Setup Modes

The test setup used to measure the transmissibility of the fluorosilicone rubber, silicone gel, and wire rope isolators was sufficient for quantitatively determining the performance of the isolators near 150 Hz. However, it clearly influenced the high frequency measurements of transmissibility. For frequencies larger than 300 Hz in Figure 6a, modes of the test setup appear and cause the transmissibility to increase and peak around 850 Hz. The mode at 850 Hz can likely be attributed to the G10 standoffs. This feature can also be seen in the measurements made for the silicone isolators and fluorosilicone rubber, further indicating the test setup has a mode at 850 Hz. The CR2-100 isolators were tested parametrically with added mass and various input voltages to investigate the modes of the test setup. These measurements were made at ambient temperature and pressure. Two different masses, 182 grams and 200 grams, were added to the 1072 gram copper puck at constant input accelerations. Also, in a separate study a 450 gram mass was added to the bottom plate and the

![Graphs](image.png)

Figure 7. Results of parametric study measuring the effect of mass and input acceleration on CR2-100 wire rope isolator performance.
input was varied. The RMS acceleration and the isolated mass are indicated on each plot in Figures 7 and 8. The 75 Hz resonance of the isolators did not vary significantly but the parametric study had a noticeable effect on the 850 Hz resonance. This result confirms that the test setup influenced the results at higher frequencies.

Titanium Flexures

Since the results of COTS isolators were not promising, custom flexures made of Ti-6Al-4V, illustrated in Figure 1d, were designed. The flexures were designed with a hard stop to limit displacement of the cryocooler during launch. In addition, they were intended to provide an order of magnitude force reduction at the cryocooler's operating frequency (135 Hz). For flight, a hexapod design is proposed to achieve a kinematic mount for the cryocooler mounting bracket. For testing, a configuration with three isolators and half the supported mass expected in flight was used. Three test isolators were built without the hard stop for simplicity and were tested in the configuration shown in Figure 9. The Labworks® shaker was connected to an upper plate through a force sensor. The three flexures connected to a base plate which was attached to a 3-axis Kistler® dynamometer. This test setup is similar to that described in further detail in Ref. [12]. In addition, this test setup was designed such that the three isolators’ axes met at the center of mass of the supported mass as shown in Figure 9b. Figure 10 shows the results of a frequency sweep at room temperature with an
input force of 0.57 Nrms. At three constant input forces between 0.57 and 1.27 Nrms the flexures show independence of input force and reached a minimum force transmissibility of 0.04 near 500 Hz. Note that this test setup has a first mode around 1100 Hz. Overall, these isolators sufficiently meet the needs of the MISE instrument.

CONCLUSION

This paper described the testing and results of various mechanical isolators and materials able to perform in harsh radiation environments and at low temperatures. Firstly, fluorosilicone rubber was not a sufficient isolating material even at room temperature. Silicone gel isolators were promising at room temperature, but the operating temperature in flight is near the materials gel-solid phase change. Wire rope isolators are a good option due to their temperature independent behavior, but COTS options may not exactly meet mission specifications. Titanium flexures show similar trends in behavior to wire rope isolators and can be designed and modeled easily to meet specifications.

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REFERENCES


