Vibration-heating in ADR Kevlar suspension systems

James Tuttle¹, Amir Jahromi¹, Edgar Canavan¹, Michael DiPirro¹, Mark Kimball¹, Peter Shirron¹, Chloe Gunderson², and Jacob Nellis²

¹NASA Goddard Space Flight Center, Code 552, Greenbelt, MD 20771 USA
²Department of Mechanical Engineering, Univ. of Wisconsin, Madison, WI 53706 USA

E-mail: james.g.tuttle@nasa.gov

Abstract. The cryogenics group at NASA’s Goddard Space Flight Center has a long-standing development and test program for laboratory and space-flight adiabatic demagnetization refrigerators (ADRs). These devices are used to cool components to temperatures as low as 0.05 K. At such low temperatures the ADR systems can provide a few micro-Watts of cooling power, so it is important to minimize the conduction of heat to these cold stages from the surroundings. The cold ADR elements are held in place by thin tensioned strings made of Kevlar, chosen for its high strength and stiffness and low thermal conductivity. During laboratory testing, we have observed that occasional significant additional heat loads on the coldest ADR stages correlate with unusually high vibration levels in the cryostat due to a noisy mechanical cryocooler. We theorized that this heat results from plastic deformation of the Kevlar fibers and frictional interactions among them, driven by the cryostat vibrations. We describe tests and calculations performed in attempt to confirm this source of the heating.

1. Introduction

NASA’s Goddard Space Flight Center has long been a leader in the development of adiabatic demagnetization refrigerators (ADRs). The cryogenics group at Goddard builds multi-stage ADR systems for space missions and for laboratory test facilities. A common configuration includes a continuous stage providing about 6 µW of cooling at 50 mK and a second stage which spends about half of its time at temperatures below 50 mK[1]. In addition to the work involved in fabricating and assembling such a system, a major technical challenge is controlling the cryogenic environment so that unwanted heat sources don’t use up some of the cooling power.

In one particular laboratory ADR, each of the coldest two stages began experiencing an intermittent excess heat load after years of facility use. At its worst, the total excess heat load was above 10 µW, and the continuous stage was unable to reach its 50 mK operating temperature. This problem was correlated with occasionally-high vibration modes of the aging mechanical cryocooler used to keep the ADR’s heat sink at about 3 K. When the cooler was powered off, the ADR was able to function for a short time before the sink temperature rose too high. While the cooler was powered off, the excess heat load disappeared. We managed the situation temporarily via minor modifications to the cryostat, but
eventually the cryocooler was returned to the vendor to have its worn seals replaced.

Because most detectors and optical elements on space instruments are very sensitive to motion, minimization of vibrations is a high priority on space missions. Thus, an ADR in space is unlikely to experience the level of vibrations that plagued our laboratory system. However, even space-flight ADRs must be tested at the sub-system level in laboratory cryostats, and the programmatic risk associated with vibration-heating is significant. Thus, we set out to study the actual source of the heating within the ADR and to explore methods of avoiding it.

In all of our ADR systems, the lowest-temperature cooling stages are held in place by tensioned Kevlar strings. The coldest two stages of the laboratory system mentioned earlier are shown in Figure 1A. The continuous 50 mK stage, on the right side of the figure, is suspended by six such legs, each about 2 cm long, from a 3 K frame. A close-up view of one leg is seen in Figure 1B. During normal operation, the total heat conducted through all six legs is less than 0.5 µW. We assumed that abnormal vibrations caused stretching and rubbing of the Kevlar fibers in each leg, resulting in heat generation. We speculated that this heating was distributed uniformly along the Kevlar length, and a simple thermal model allowed us to predict each leg’s temperature profile and the resulting heat flow at the cold end of each support leg for a given linear heat density. The model indicated that heat loads of several µW would cause a measurable rise in the midpoint temperature of each leg. Armed with this information, we set out to test the uniform heating assumption as the first step toward understanding our problem and its possible solutions.

2. Test Set-up

We assumed that vibration-heating generated in the Kevlar would be measurable at typical cryostat temperatures of about 4 K, so our test would not require an actual ADR stage at lower temperatures. Our approach was to suspend a cylindrical dummy mass from a support frame in a nearly identical configuration to that of the lab ADR’s continuous stage. The frame was mounted via a weak thermal link above our 4 K test cryostat’s cold plate. Thermometers and resistive heaters on the dummy mass and frame allowed each to be independently temperature controlled, and the dummy mass heater power was precisely measured with a volt meter and an ammeter. A tiny thermometer was installed at the midpoint of one Kevlar support leg. In the test configuration, any vibration heating reaching the dummy mass resulted in a drop in its control heater power, and this heat could be correlated with any measured
Figure 2. A. The test set-up for our measurement. Arrows indicate the locations of thermometers and heaters on the frame and suspended dummy mass and the location of Kevlar thermometer. B. A close-up view indicating the details of the tensioned Kevlar leg configuration.

rise in the Kevlar midpoint temperature.

Figure 2 shows the details of the dummy mass suspension, which matched that of the lab ADR’s continuous stage, and the locations of heaters and thermometers. The ends of each Kevlar leg were epoxied inside axial holes in a small screw and a threaded stud. The screw fit inside a hole in a flange on the dummy mass, with a stack of Belleville washers under its head. Each Kevlar leg was tensioned by tightening a nut on the stud and monitoring the compression of the Belleville stack. Achieving proper equal tension on all six legs was difficult, and we ended up breaking and re-making several of the Kevlar legs. Thus, in our first test configuration we set the Kevlar tension lower than in the laboratory ADR. Copper-wire thermal straps, not shown in the figure, connected the support frame to the cryostat’s cold plate and to the dummy mass. These straps, which allowed our test apparatus to cool down in a reasonable time, were attached close to the heater locations in order to minimize temperature gradients in the frame and dummy mass.

The Kevlar-mounted thermometer was a tiny bare-chip Cernox sensor, purchased from LakeShore Cryotronics. We soldered 64 µm diameter stainless steel leads onto the thermometer’s copper terminal wires in a 4-wire twisted pair configuration. We slid the sensor between the midpoint of the fibers of one Kevlar leg before tensioning it. When the leg was tensioned, the fibers grabbed the thermometer’s copper terminal wires. We added a dot of epoxy to the attachment point to improve thermal contact with the Kevlar, and a similar epoxy dot at the midpoint of each other leg ensured that they were thermally symmetric. The thermometer’s thin stainless steel current and voltage leads were attached to a temperature-controllable stage about 20 cm away from the Kevlar attachment point. This was done so that we could eliminate any temperature drop and resulting heat flow along the leads. However, during our testing the indicated thermometer temperature proved to be independent of this stage temperature, so we did not need to control it.

We produced vibrations using a transducer designed for installation in the seat of a home movie theater. This device was driven by current from a high-power sine-wave generator. We originally tried to modify the transducer so that it could be mounted on the cryostat cold plate and attached directly to the support frame. However, its coil and leads heated up and produced thermal radiation absorbed by the dummy mass and the Kevlar thermometer. This was unacceptable, since we were hoping to resolve a few µW of vibration heating. We eventually mounted the transducer on the outside of the cryostat’s room temperature vacuum shell, and the vibrations were transmitted through the cryostat’s internal structure to its cold plate. The transducer was positioned on an edge of the cryostat’s flat top plate. In this location it primarily produced a rocking motion in the vacuum shell, which hangs from a support
dolly that allows it to be inverted.

A secondary goal of this effort was to measure the amplitude of the dummy mass’s sinusoidal displacement relative to the frame during the testing. For this purpose, we purchased a three-channel Attocube model IDS3010 displacement sensor. Each channel of this system uses an infrared laser beam to measure the distance from a small sensor head to a reflecting surface at frequencies up to 1 MHz. The fiber-optic connection between each head and the controller box passes through a hermetic interface, allowing the heads to be installed inside a vacuum chamber. We purchased heads which were compatible with cryogenic temperatures and installed them in our test cryostat. We designed holders for the heads which allowed them to be tilted in two directions, and we installed these holders on the support frame. Two of the heads were positioned so that they aimed in perpendicular horizontal directions toward the vertical central axis of the cylindrical dummy mass. One of these channels was parallel to and the other perpendicular to the cryostat’s rotation axis. A third head aimed downward toward the mass’s flat top surface. Small squares of aluminized tape were positioned on the dummy mass to act as reflectors. The distance from each head to its reflector was approximately 2 cm. Figure 3A indicates the locations of the heads and corresponding reflectors, and Figure 3B is a photograph of the entire apparatus.

We spent a significant amount of time getting the Attocube system to work in this application. The displacement sensing requires a critical fraction of the reflected beam to re-enter the head, otherwise it fails to produce a signal. Since Kevlar’s stiffness changes when it is dried out in a vacuum, the dummy mass’s position and angle changed slightly when the cryostat was evacuated. Further shifting occurred when the cryostat was inverted and cooled to its operating temperature. This was a minor problem for the vertical sensing head, but it had a significant effect on the return angle of the two horizontal beams, which reflected off a curved surface. After several unsuccessful attempts to get signals from the horizontal heads at cryogenic temperatures, we replaced the aluminized tape with small dots of retro-reflecting tape. This improved the situation somewhat, but the retro-reflective tape’s adhesive was thick and soft and did not turn out to be very compatible with a vacuum and cryogenic environment. We are currently exploring other options for retro-reflectors for the horizontal channels.

3. The First Data Run

We monitored the Attocube displacement readings occasionally during the two-day cooldown preceding our first data run, as well as a real-time Fast Fourier Transform (FFT) signal provided by the readout software. Unfortunately, the two horizontal channels ceased reading when the dummy mass reached about 20 K, and we later discovered that the retro-reflective dots had fallen off. The vertical channel
continued to read properly throughout the run. The FFT signal indicated several vibration resonances, including a cryocooler mode with amplitude of about 100 nm at 30 Hz. However, because the sensor heads were mounted on the support frame, most modes reaching the apparatus drove the frame and dummy mass simultaneously and did not result in significant relative displacement. This common-mode rejection was helpful, as the sensor only measured motion associated with stretching of the Kevlar legs.

We learned that the laser beam produced a significant heat load on the dummy mass and caused a temperature rise in the Kevlar thermometer. Thus, we powered off the Attocube device during our vibration heating data acquisition and turned it on later to measure the dummy mass motion for each of the transducer excitation current values we had used.

The apparatus cooled down to 5 K, and we calibrated the Kevlar thermometer in situ between 5 and 9 K by controlling the frame and dummy mass at several pairs of temperatures 10 mK apart. At each such point we waited for the Kevlar sensor’s resistance to reach a steady value and then assumed that it was midway between the frame and mass temperatures. We decided to control the frame at 6 K and the dummy mass at 6.01 K, as these temperatures resulted in a zero-vibration dummy mass control power of about 40 µW. Note that these are only indicated temperatures, and that the calibration curves provided by LakeShore Cryotronics have uncertainty of a few mK at these temperatures. By optimizing the temperature controller box gain and time-averaging over a few minutes, we were able to resolve this control power to within about 0.2 µW. In preparation for our experiment, we re-ran our uniform-heating Kevlar thermal model to predict correlated midpoint temperature and dummy mass heating values with these two Kevlar endpoint temperatures.

Experimenting with the transducer, we found that there was a narrow mode at 128 Hz which both heated the dummy mass and drove up the Kevlar midpoint temperature significantly. We applied several different sinusoidal current values to the transducer, waiting several minutes each time until the power and temperature reached steady values. The data, shown in Figure 4, were well-behaved for excitations which drove the Kevlar temperature up by less than about 0.4 K. In this range they also matched the model prediction quite well, supporting our supposition that the heating occurs uniformly along the Kevlar lengths. However, for larger excitations the dummy mass power jumped to much higher values which were only quasi-stable. We spent more than an hour waiting for the single point in that range shown in the figure. It was obvious that we had seen the onset of a different mode of heating the dummy mass.

![Figure 4](image_url)

**Figure 4.** Data from the first run taken at 128 Hz. The orange line is the prediction of the model assuming uniform heating along each of the six Kevlar legs. The data error bars are mostly obscured by the plotted dots. For Kevlar temperature rises above about 0.4 K the data were unstable. The one point plotted in that region was quasi-stable.
We powered on the Attocube sensor and measured the RMS vertical deflection of the dummy mass relative to the frame for each of the transducer excitation currents from our data set. Figure 5 shows the dummy mass power and the Kevlar temperature rise plotted against this deflection. It is clear that the highest temperature rise point, although slightly less stable than the lower values, follows the same trend as a function of the deflection. The dummy mass heating, however, rose by a factor of almost 8 between its highest two values. This suggests that the additional heating seen in the last point is not associated with the Kevlar, and we speculated that it was due to the onset of friction or chattering in the Belleville washer stacks. It is not clear whether this had happened in the original observed laboratory ADR heating, since our Kevlar tension may have been less than that in the ADR. However, where possible we plan to move the tensioning springs to the warm end of each Kevlar leg in future suspension designs.

After the first test run was completed we enlisted the aid of a structural analyst to study our test setup. He found that his non-linear finite-element model was somewhat sensitive to small asymmetries in the dummy mass, which might be caused by the added heater, thermometer and thermal strap wire. Ignoring these effects, his model predicted resonant modes at 94 Hz in which the dummy mass tilted relative to the stationary support frame. These modes stretched all six Kevlar legs approximately equally, which is consistent with the assumptions of our thermal model. The fact that our actual resonance was found at 128 Hz could be due to uncertainty in the stiffness of the Belleville stacks and the Kevlar, as well as to asymmetries in the dummy mass.

The cryostat was warmed to room temperature so that modifications could be implemented before the second data run. Figure 6 shows these changes graphically. The six Kevlar leg assemblies were re-
Figure 6. Changes in the Kevlar leg assemblies were implemented between our first and second data runs.

made with the same Kevlar lengths, but longer threaded studs at the frame ends. The Belleville washer stacks were replaced by cylindrical stainless steel spacers under the screw heads. A standard compression spring was installed between each nut and the support frame, and tensioning of each leg involved tightening its nut while holding the outer end of the threaded stud. After tensioning the Kevlar legs, fresh retro-reflective circles were installed with dots of epoxy around their edges to keep them from falling off during cooldown. Because of the small surface area on the frame attachment points, the available commercial springs were much less stiff than the stacks of Belleville washers they replaced. This necessitated much more motion of the dummy mass to achieve the same Kevlar elongation, and the springs shifted in position during vibration trials performed at room temperature. Much time was spent tweaking the spring positions to find a configuration that survived room temperature evacuation with all three Attocube channels still reading properly. We were not confident in the stability of the system, but we decided to try a data run before pursuing further modifications.

4. The Second Data Run
We cooled down the cryostat for the second data run, again monitoring the status of the three Attocube channels. This time one of the horizontal channels failed to operate at our test temperature, and the other horizontal channel worked only intermittently. Again, the vertical channel performed reliably throughout the run.

We found a resonance at 195 Hz which produced responses in the dummy mass power and the Kevlar temperature. We took two data points at this frequency, shown as red squares in Figure 7. One of these points used the maximum possible transducer excitation current with our configuration at that time, producing a deflection of 2200 nm, while the other used 2/3 of that current. We were surprised to find that the dummy mass power values were almost exactly half of the model predictions for the observed Kevlar temperature rises.

In an attempt to increase the amplitude of vibrations, we added a second transducer, wired in series with the original one. Another promising frequency was 25 Hz, and we raised the transducer current over several steps up to 2/3 of its maximum value. The resulting data are green circles in Figure 7. The first two points matched the thermal model reasonably well, but the third point jumped to a significantly higher Kevlar temperature and a dummy mass power well above the model prediction. For two higher excitations the power rose rapidly for moderate increases in the Kevlar temperature. After taking an overnight break, we attempted to take more data at 25 Hz. However, we now found the results to be unstable over the entire range of excitations. Clearly something had changed in our apparatus during or after acquiring the highest plotted point on Figure 7. We have yet to open the cryostat for inspection.

Our structural analyst modeled the system configuration with the soft springs. At approximately 180
Hz he found two modes in which the dummy mass was stationary and the support frame tilted relative to its one constrained end. This resulted in Kevlar elongation only for the three legs attached to the frame’s unconstrained end, and our Kevlar thermometer is located on one of these legs. If one of these modes is the one we observed at 195 Hz, it would explain why the dummy mass power was exactly half of that predicted by the thermal model. The model also predicted a tilting mode for the dummy mass at 19 Hz, a bouncing mode at 24 Hz, and a rotating mode at 21 Hz. All of these modes caused uniform elongations of the six Kevlar legs. It is possible that these modes are somewhat coupled, and our unstable results at 25 Hz might result from transitions among these modes.

5. Conclusion
This work represents the beginning of our efforts to study vibration-heating in our suspension systems. It is clear that we need to improve our retro-reflectors for future testing, and we are exploring the possibility of using small corner cubes for this purpose. The data so far suggest that we should lock spacers and springs in place at the ends of our suspension legs, perhaps with epoxy, to avoid frictional motion. Our next step is to replace the soft springs with designed-for-space-flight flexures, which will be significantly stiffer and more structurally stable than the springs. The goal is to characterize Kevlar heating up to higher power values, with similar resolution to that achieved in these early tests. We hope that a precise measurement of the Kevlar heating as a function of its displacement will give a better understanding of the heating mechanism and help us to explore possible ways of mitigating the effect.

References
[1] Shirron P et al. 2005 Proc. SPIE 5904 5904W.

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