Characterization Testing of Space-Flight Lockheed Martin Micro 1-2 Cryocooler for the Mapping Imaging Spectrometer for Europa (MISE)

I.M. McKinley, M.A. Mok, and J.I. Rodriguez

Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109

ABSTRACT

The Mapping Imaging Spectrometer for Europa (MISE) instrument on the Europa Clipper mission uses a Lockheed Martin "high-power" Micro1-2 pulse tube cryocooler with a heat rejection temperature around 220 K to provide cooling at 80 K. This paper describes the thermal performance and exported forces characterization testing and results of the space-flight Lockheed Martin Micro1-2 cooler optimized for these conditions. Prior to these characterization tests, the cooler passed random vibration and thermal vacuum cycling at Lockheed Martin.

INTRODUCTION

A Lockheed Martin Micro1-2 cryocooler will provide active cooling on the Mapping Imaging Spectrometer for Europa (MISE) Instrument on NASA's Europa Clipper spacecraft. The MISE Micro1-2 coaxial pulse tube microcryocooler flight model (FM) weighs 477 grams including the compressor pedestal mount. This model is slightly larger than the 350 gram, 25 W standard version (Micro1-1) that has been thoroughly characterized previously [1, 2, 3, 4, 5]. The Micro1-2 cooler can be driven with up to 60 W and its performance at various heat rejection temperatures was measured and was previously reported [6, 7, 8, 9, 10, 11, 12]. MISE intends to reduce power consumption of the cooler by taking advantage of its functionality at 220 K which is much lower than the 300 K for which it was optimized. As a result, a Micro1-2 MISE prototype cooler was developed. It was optimized to operate at 135 Hz with a 220 K heat rejection temperature to provide 0.75 W of cooling at 80 K. MISE procured two prototype (PT) units of this model of cooler from Lockheed Martin. The left photograph in Figure 1 shows one of these prototype coolers. These prototype coolers were identical except for the helium fill pressure. Proto1 was tested at two different fill pressures, namely 800 psi and 600 psi while Proto2 remained at 750 psi throughout the testing.

The right photograph in Figure 1 shows the MISE FM cooler. After the assembly of the FM cooler, Lockheed Martin performed proof pressure testing to 1200 psi, then filled the cooler to 725 psi. After the final helium fill, workmanship random vibration to the GEVS PF levels [13] and limited thermal cycling were performed. After the completion of these tests, Lockheed Martin shipped the cryocooler to the Jet Propulsion Laboratory (JPL) where characterization tests were performed. This paper describes the tests performed at JPL.

Cryocoolers 21, edited by R.G. Ross, Jr., J.R. Raab and S.D. Miller

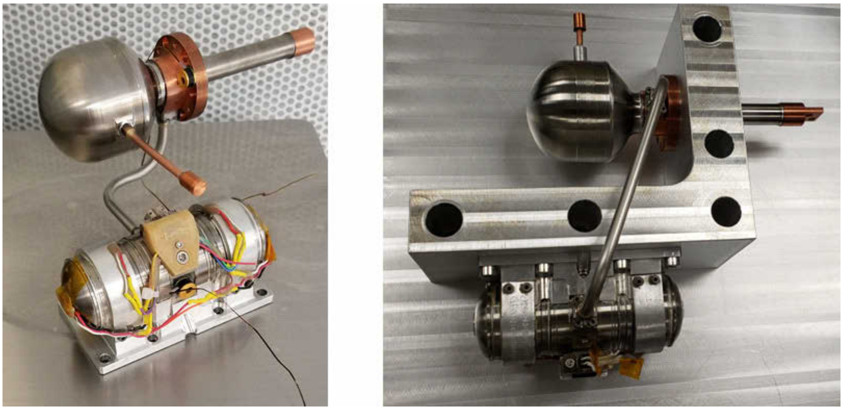


Figure 1: Left: MISE prototype cryocooler. Right: MISE FM cooler.

THERMAL PERFORMANCE TESTS

Test Setup and Procedure

Figure 2 shows the MISE FM cooler in the thermal vacuum (TVAC) chamber at JPL. The test setup was very similar to the one previously used and described in Ref. [5]. In this case, the cooler was mounted to an aluminum plate that was connected to a CTI 350 coldhead by means of a copper bar. All of the cold surfaces including the microcooler cold finger were wrapped in multi-layer insulation (MLI) of aluminized mylar. The cold tip temperature was measured by two Lakeshore DT-670 diodes and controlled by a Lakeshore 336 temperature controller powering a resistive element. Both the heater and sensor were attached to a copper block that was clamped to the cold tip and made use of four-wire measurements. Prior to the cooler operation, its helium leak rate was measured to be $1.8x10^{-9}$ mbar·L/s.

The cooler was powered using a Chroma 61602 AC source supplying between 10 W and 23 W at frequencies between 118 Hz and 144 Hz. The heat rejection temperature was defined as that of the expander mounting flange of the microcooler. It varied from 195 K to 250 K while the cold tip temperature varied from 80 K to 250 K. The compressor temperature was as much as 20 K warmer than the expander temperature during these tests. It has been previously shown that the cooler performance is independent of compressor temperature for a fixed expander temperature [12]. In addition, Lockheed Martin operated the cooler up to 40 W during their thermal cycling testing; some of this data is included in the following sections of this document. Finally, the cooler underwent cold starts at 180 K during this testing with voltages up to 15 V_{rms} at 135 Hz to test for loss of clearance between the pistons and their end-stops. No loss of clearance was observed. The corresponding power at 15 V_{rms} was 40 W. Note that this same result may not have been observed if the cooler was driven at a lower drive frequency closer to the optimal frequency at 180 K.

Performance at 80 K

Frequency Sweeps. Figure 3 shows the specific power of the FM cooler vs. drive frequency for 20 W input power and 80 K cold tip for different expander temperatures. The specific power was defined as the compressor input power divided by the cooling power. For a given heat rejection temperature, the drive frequency that yields the minimum specific power corresponds to the optimal drive frequency. It is evident that the optimal drive frequency was dependent on the heat reject temperature. In fact, the optimal frequency varied linearly with expander temperature. In addition, the specific power decreased with decreasing expander temperature indicating that the cooler had higher thermodynamic efficiency at lower heat rejection temperatures. Furthermore, as the expander temperature decreased, the specific power was less dependent on drive frequency. For example, at 195 K expander temperature the specific power varied by 1 W/W over an 8 Hz range, whereas it varied by 5 W/W at 250 K expander temperature. Finally, the frequency sweeps that Lockheed Martin

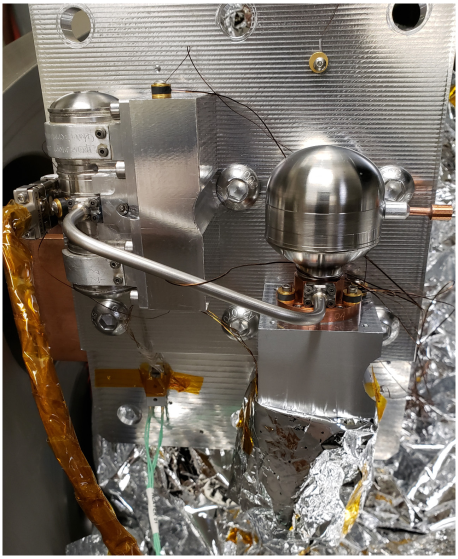


Figure 2: TVAC performance test setup.

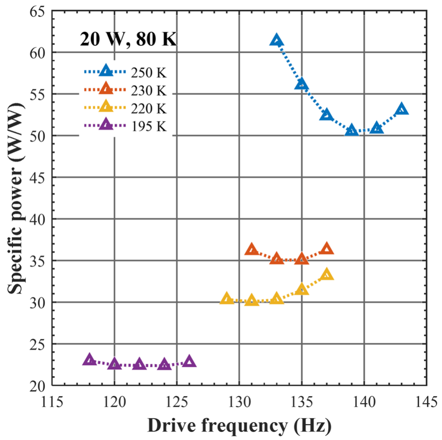


Figure 3: Specific power vs. drive frequency for different heat rejection temperatures with the cold tip at 80 K and 20 W of compressor power.

performed at 30 W input power and 80 K cold tip indicated that, for a given expander temperature, the optimal frequency was independent of input power between 20 W and 30 W.

Performance at Optimal Frequency and 135 Hz. Figure 4 shows compressor input power vs. heat lift for various expander temperatures with an 80 K cold tip and the cooler driven at its optimal drive frequency shown in Figure 3. The data points for compressor input power of 30 W or greater were measured at Lockheed Martin during thermal cycling testing. It is evident that, as the expander temperature increased, there was less heat lift for a fixed compressor temperature. Figure 5 shows the specific power vs. compressor input power for the same data contained in Figure 4. It illustrates that the specific power decreases with increasing compressor input power. It also illustrates that, as the expander temperature increases, the compressor power has a larger effect on the specific power.

In flight, the cooler will nominally be operated at 135 Hz throughout the mission. Figure 4 and Figure 5 also show data measured for the cooler operating at 135 Hz. They illustrate the performance and efficiency of the cooler at 135 Hz. The environmental temperatures of each Europa fly-by are different and the expander temperature is not actively controlled. Depending on the specific fly-by, it is expected to be anywhere from 220 K to 250 K during steady-state operation. In this temperature range, operating at 135 Hz does not greatly affect the performance or efficiency of the cooler.

Performance During Cool Down

In flight, the cooler will be at least 195 K before being powered on. Once powered on, it will operate with 12 Vrms applied to the compressor motors until it reaches an 80 K cold tip setpoint. Once the setpoint is reached, the cryocooler electronics will reduce the voltage to the motors to maintain the setpoint. The expander temperature is not actively controlled during cool down. Figure 6 shows the compressor input power vs. cold tip temperature for the cooler driven at 135 Hz with 12 V_{rms} for various expander temperatures. It is evident that, as the cold tip decreased, the compressor power increased. In addition, for a fixed cold tip temperature, the compressor power increased for decreasing expander temperature. Figure 7 shows the heat lift vs. cold tip temperature for the cooler driven at 135 Hz with 12 V_{rms} for various expander temperatures. The heat lift increased for increasing cold tip temperature and decreasing expander temperature.

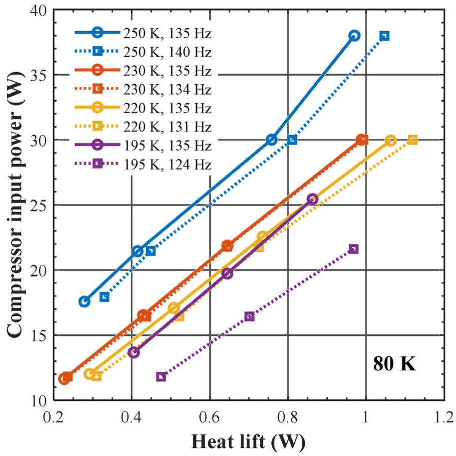


Figure 4: Compressor input power vs. heat lift for 135 Hz and the optimal drive frequency for various expander temperatures with an 80 K cold tip.

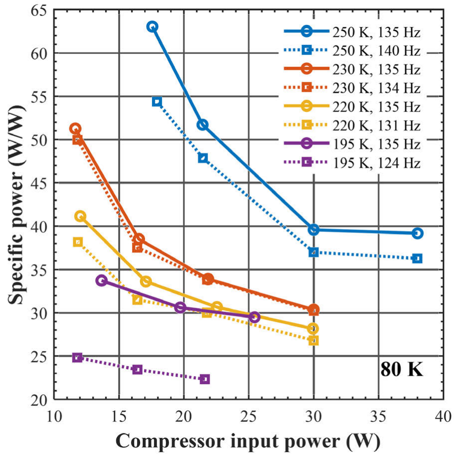


Figure 5: Specific power vs. compressor input power for 135 Hz and the optimal drive frequency for various expander temperatures with an 80 K cold tip.

EXPORTED FORCES AND TORQUE

Test setup and Procedure

Figure 8 shows a photograph of the FM cooler mounted on a Kistler dynamometer. This setup was very similar to that previously used in Ref. [5, 9] and described in detail in Refs. [14, 15]. The cooler was operated near room temperature and the cold tip was held under vacuum. Steady-state force and torque measurements were made for input power varying from 5 W to 53 W and frequency varying from 129 Hz to 160 Hz. The axes were defined such that the compressor axis was along the direction of piston motion, the radial parallel-to-mount was aligned with the gravity vector, and the radial normal-to-mount axis was orthogonal to the others. The cooler was driven with a Chroma 61602 AC source.

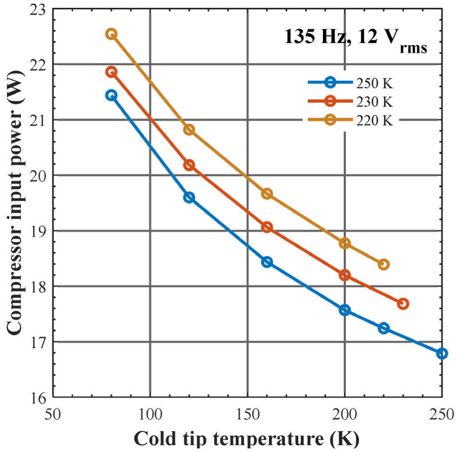


Figure 6: Compressor input power vs. cold tip temperature for the cooler driven at 135 Hz with 12 Vrms for various expander temperatures.

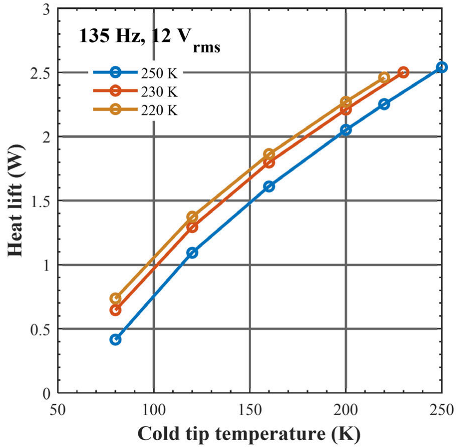


Figure 7: Heat lift vs. cold tip temperature for the cooler driven at 135 Hz with 12 Vrms for various expander temperatures.

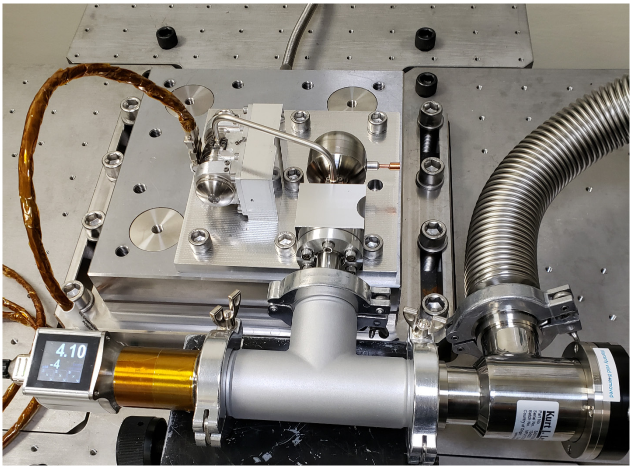


Figure 8: Photograph of the FM cooler mounted to the dynamometer.

Effect of Drive Frequency

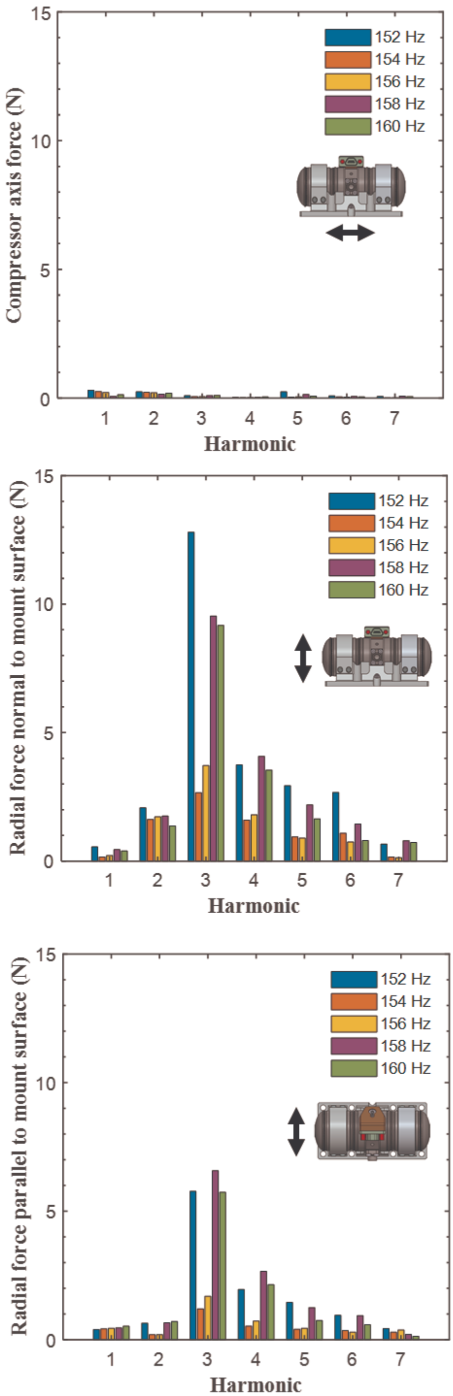
Figure 9 and Figure 10 show the 0-peak exported forces from the FM cooler in all three axes as a function of harmonic for various drive frequencies with 30 W and 47 W compressor power, respectively. Figure 9 indicates that the largest forces were in the compressor radial axis normal to the mounting surface. These large forces are due to an internal resonance in the compressor near 480 Hz when the piston amplitude is 1 mm [10]. When the cooler is near room temperature, the most efficient drive frequency is around 155 Hz and 30 W of compressor input power yields a 1 mm piston amplitude. However, when the cooler is operated near room temperature at lower frequencies, it is inefficient and thus higher compressor power is needed to achieve a 1 mm piston amplitude. In fact, 47 W yields a piston amplitude of 1.1 mm at 135 Hz. Figure 10 illustrates that the cooler has nearly a factor of ten lower forces at drive frequencies near 135 Hz than drive frequencies near 156 Hz for the same piston amplitude.

Effect of Piston Amplitude

Figure 11 shows the 0-peak exported forces as a function of piston amplitude and harmonic in all three axes for the cooler driven at 135 Hz. In general, the forces increased with increasing compressor input power/ piston amplitude. The piston amplitude was not measured directly but was interpolated from measured piston position data from the Proto1 cooler. For 800 psi and 600 psi fill pressures, the piston amplitude vs. compressor input power was fit with a 2nd order polynomial and then the coefficients were fit linearly as a function of helium fill pressure. The growth of the forces was generally linear with increasing piston amplitude indicating that structural resonances were not excited.

CONCLUSION

This paper described the thermal performance and exported vibration testing and results of the MISE Flight Model Lockheed Martin Micro1-2 pulse tube cryocooler. This cooler will be used on the MISE Instrument on the Europa Clipper mission. The thermal performance of the microcooler was measured in vacuum for heat reject temperatures between 195 K and 250 K. The coolers were operated at input powers ranging from 10 W to 23 W and drive frequency between 118 Hz and 143 Hz. The optimal drive frequency was dependent on heat reject temperature. In addition, the exported forces and torques of the coolers were measured at 300 K heat rejection for input powers ranging from 5 to 53 W and drive frequency between 129 and 160 Hz. The exported forces were



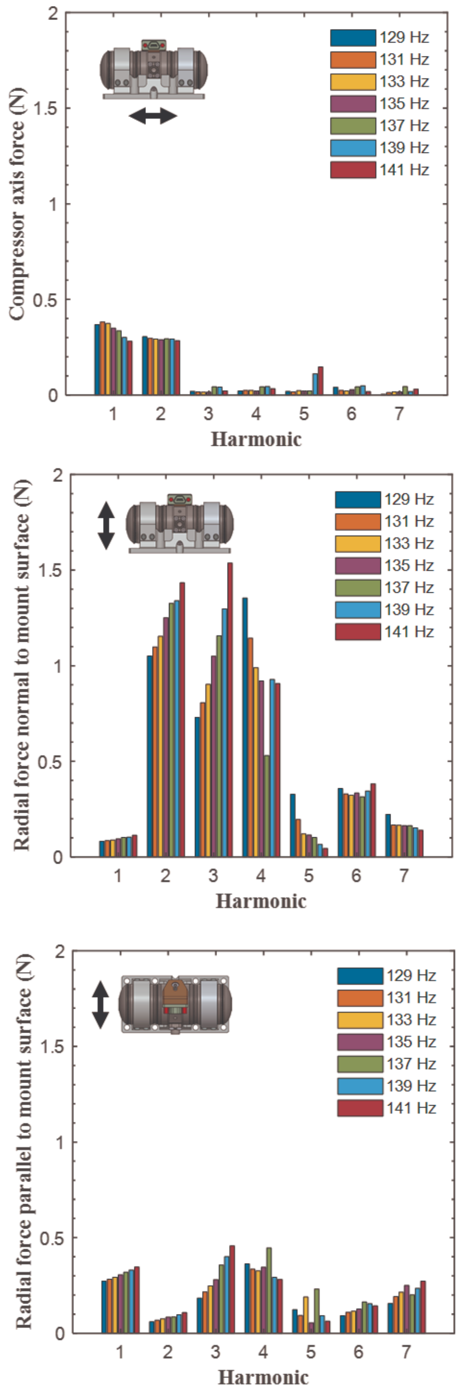


Figure 9: 0-peak exported forces in all axes with 30 W into the cooler for various drive frequencies.

Figure 10: 0-peak exported forces in all axes with 47 W into the cooler for various drive frequencies.

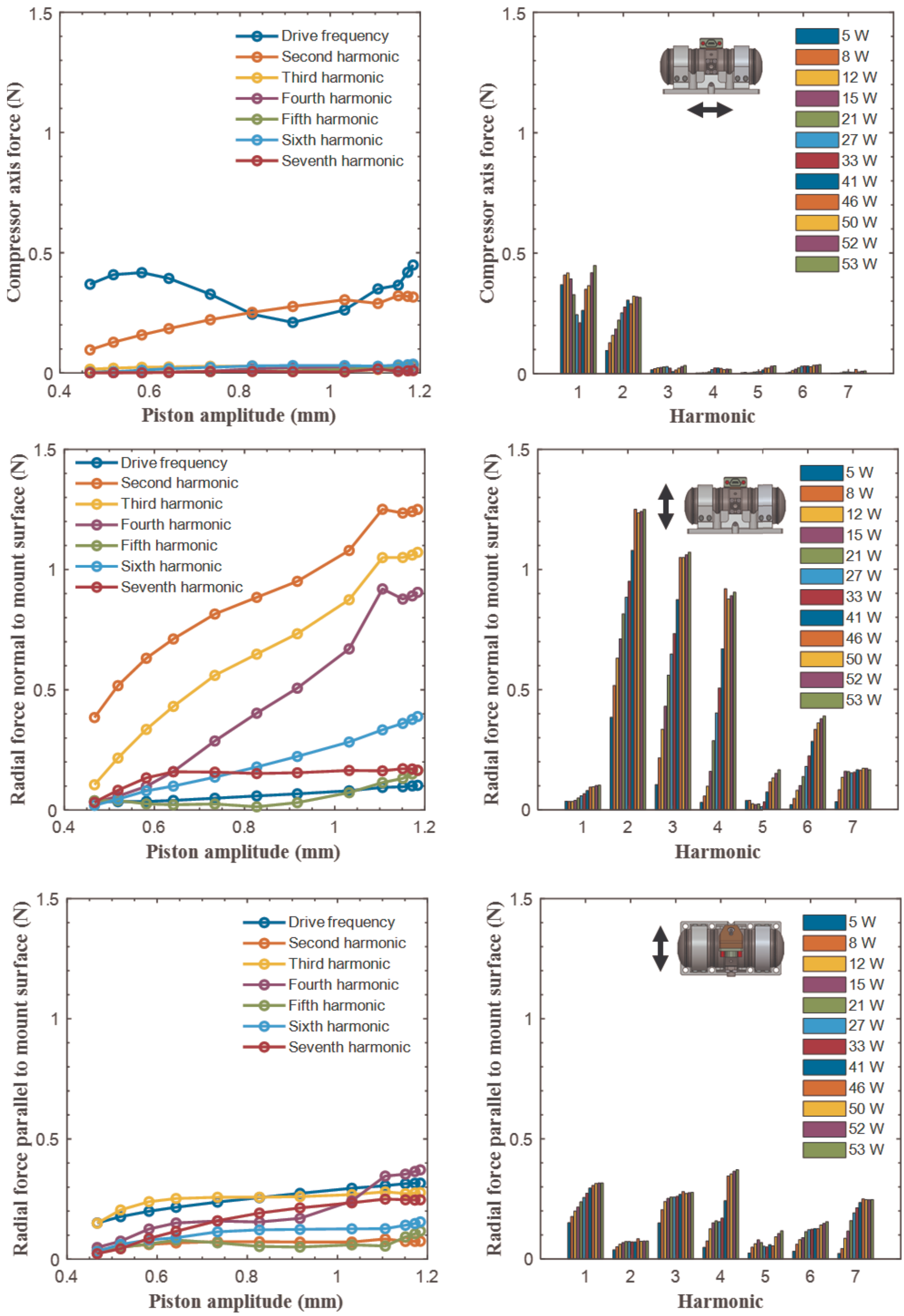


Figure 11: 0-peak exported forces in all axes as a function of piston amplitude and harmonic for various input powers at 135 Hz.

dependent on both piston amplitude and drive frequency. Overall, this flight model cooler met the requirements and needs of the MISE Instrument.

ACKNOWLEDGMENT

The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the National Aeronautics and Space Administration. In addition, the authors would like to thank Liz Osborne and Jeff Olson of Lockheed Martin, as well as Dean Johnson, Kirsten Maynard, Chris Wollonciej, John Kennedy, Carl Bruce, and Diana Blayney of JPL for their contributions to this work.

REFERENCES

1. T. Nast, E. Roth, J. Olson, P. Champagne and D. Frank, "Qualification of Lockheed Martin micro pulse tube cryocooler to TRL6," *Cryocoolers 18*, ICC Press, Boulder, CO, 2014
2. J. Olson, G. Kaldas, P. Champagne, E. Roth and T. Nast, "MatISSE Microcryocooler," *IOP Conf. Series: Materials Science and Engineering 101*, 2015.
3. J. Olson, P. Champagne, E. Roth, G. Kaldas, T. Nast, E. Saito, V. Loung, B. McCay, A. Kenton and C. Dobbins, "Coaxial Pulse Tube Microcryocooler," *Cryocoolers 18*, ICC Press, Boulder, CO, 2014.
4. J. Olson, P. Champagne, E. Roth, T. Nast, E. Saito, V. Loung, A. Kenton and C. Dobbins, "Microcryocooler for tactical and space applications," *AIP Conference Proceedings 1573, 2014.*
5. I. McKinley, D. Johnson and J. Rodriguez, "Characterization Testing of Lockheed Martin Standard Micro Pulse Tube Cryocooler," *Cryocoolers 18*, ICC Press, Boulder, CO, 2016.
6. D. Frank, P. Champagne, E. Will, G. Kaldas, L. Sanders, E. Roth and J. Olson, "Extended range of the Lockheed Martin coax Micro cyrocooler," *Cryogenics*, pp. 55-58, 2016.
7. T. Nast, J. Olson, P. Champagne, E. Roth, E. Saito, V. Loung, B. McCay, A. Kenton and C. Dobbins, "Development of Microcryocoolers for Space and Avionics Applications," *Cryocoolers 18*, ICC Press, Boulder, CO, 2016.
8. J. Olson, E. Roth, L.-S. Sanders, E. Will and D. Frank, "Lockheed Martin Microcryocoolers," *Proceedings SPIE 10180, Tri-Technology Device Refrigeration*, Anaheim, 2017.
9. I. McKinley, C. Hummel, D. Johnson and J. Rodriguez, "Characterization testing of Lockheed Martin high-power micro pulse tube cryocooler," *Cryogenic Engineering Conference*, Madison, 2017.
10. I. McKinley, M. Mok, D. Johnson and J. Rodriguez, "Characterization Testing of Lockheed Martin Micro1-2 Cryocoolers Optimized for 220 K Environment," *Cryocoolers 18*, ICC Press, Boulder, CO, 2018.
11. J. Olson, E. Roth, E. Will, M. Guzinski, A. Ruiz, I. McKinley, D. Johnson, J. Rodriguez and K. Frohling, "Maturation and Status of the Lockheed Martin Micro1-2 Cryocooler," *Cryocoolers 18*, ICC Press, Boulder, CO, 2018.
12. I. McKinley, M. Mok, C. Hummel, D. Johnson and J. Rodriguez, "Characterization Testing of Lockheed Martin Micro1-2 Cryocoolers for the Mapping Imaging Spectrometer for Europa (MISE) Instrument," I*OP Conference Series: Materials Science and Engineering*, Hartford, 2019.
13. GSFC-STD-7000,*General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects*, NASA Goddard Space Flight Center, Greenbelt, MD, April 2005.
14. D. Johnson, I. McKinley and J. Rodriguez, "Flight Qualification Testing of the Thales LPT9510 Pulse Tube Cooler,"*Cryocoolers 18*, ICC Press, Boulder, CO, 2014.
15. D. Johnson, I. McKinley, J. Rodriguez, B. Carroll and H. Tseng, "Characterization testing of the Thales LPT9310 pulse tube cryocooler," *Cryocoolers 18*, ICC Press, Boulder, CO, 2014.