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Advances in cryocooler control electronics for linear cryocoolers

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Abstract. Linear cryocoolers are being used for space sensor cooling for multiple proliferated and strategic space missions. The cooling, lifetime and cost requirements are unique to each mission. Multiple commercial or build-to-print versions of the mechanical cryocooler exist, but the development of mating and optimized cryocooler control electronics has lagged the mechanical cryocooler. To address this need, Creare and West Coast Solutions have developed a line of cryocooler control electronics with a modular and adaptable topology to optimally meet most future mission needs. Over the last few years, the product line has matured from a single model optimized for low-cost LEO missions and for cryocoolers with 80 to 100 W of input power to multiple models that address the lifetime, radiation, power, bus voltage ranges and jitter requirements of most future space and air-borne missions, and has achieved technology readiness level of 9 on multiple programs. In this paper, we review the current product line and present emitted vibration results obtained with a Sunpower Cryotel MT cryocooler our cryocooler control electronics with active vibration control.

1. Background

Since 1991 Creare has been developing electronics to drive multiple types of cryocoolers, including turbo-Brayton, Stirling, Pulse Tube, and Joule-Thomson varieties.[1],[2] In 2017 Creare, with our development partner West Coast Solutions (WCS), started development of a midrange variant that balances cost and technical metrics for cost-sensitive, “tactical space” (TS) missions.[3] The result of this effort, the MCCE-TS, was developed under NASA SBIR and Creare IR&D funding. The MCCE-TS is intended for radiation-tolerant, cost-sensitive space missions where commercial electronics do not meet the mission assurance and/or environmental requirements. These electronics were designed to meet typical space requirements for NASA Class C/D missions, including NASA GSFC-STD-7000A GEVS launch and environmental requirements. The original NASA Class C/D target is highly consistent with the needs of the emerging Department of Defense (DoD) and commercial markets for proliferated satellites.

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2. Technical development and features

Since the original MCCE-TS program, Creare and WCS have continued to develop versions of the MCCE optimized for specific missions, orbits and programs. Enhancements demonstrated and implemented in the product line include:

- Ripple filters (passive and active designs). The active ripple filter design includes integrated boost conversion, allowing operation of higher power cryocoolers and/or operation with lower input bus voltage.
- Launch lock. Most products include optional launch lock to protect the cryocooler and circuitry from damage due to launch shock and vibration.
- Active vibration control. This is an optional subsystem that uses active vibration control algorithms and either accelerometers or load washers to provide feedback to either opposed compressor motors or a separate balancer.
- Autonomous cooldown. We have implemented algorithms that allow the cooldown rate to be tailored while observing temperature-dependent performance limits on cryocooler operation, both minimum and maximum allowable power limits, as applicable.
- Upgraded power level. The original MCCE-TS was designed to drive cryocoolers with maximum input power of nominally 80 W (40 W/channel). Several models have been developed and demonstrated for operation of up to 160 W for use with higher capacity cryocoolers.
- Increased radiation tolerance. The original MCCE-TS utilizes electronic components with a minimum total ionizing dose (TID) rating of 30 kRad(Si). More radiation hardened versions have been developed with minimum TID of 100 kRad(Si). The box-level TID rating is higher, based on wall thickness. It should also be noted that Single Event Effect (SEE) immunity has been considered in the part selection with the higher TID version also featuring higher latch-up thresholds, lower upset rate, etc.
- Multiple-unit synchronization. This feature enables synchronization to either a master bus controller or allowing multiple CCEs to synchronize their operation.
- Compact design. For low-power applications, the C3E variant of the MCCE is optimized for reduced Size, Weight and Power (SWaP).

Additionally, several enhanced features are currently under development at a TRL 3-4 level and will be considered for sales as a product when demonstrated at a TRL of 5. All MCCE models are designed to be flexible in enclosure design and can be customized to user-specific electrical and mechanical interfaces.

3. Available MCCE models

The product family can be divided into six (6) designs with different features as follows.

1. The MCCE-TS1 design is the first-generation MCCE-TS with launch lock and passive ripple filter components. This design is currently at a TRL of 9.
2. The MCCE-TS2 design is the second-generation MCCE-TS with accelerometer-based active vibration control. This design is currently at a TRL of 9.
3. The MCCE-HP1 design is a higher-power version of the MCCE-TS2 that includes higher capacity motor drive and active ripple filter circuits, allowing operation of cryocoolers up to 160 W in total power. This design is currently at a TRL of 5, with

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engineering models of this design successfully demonstrated in high-altitude ballooning applications. This design is scheduled to achieve a TRL of 6 in 2025.

4. The MCCE-HP1+ design enhances the MCCE-HP1 design with higher radiation tolerance and an upgraded active vibration control subsystem capable of operation with force transducers. This design is currently at a TRL of 5.
5. The MCCE-C3E is a low-power, single-channel output system designed and optimized for use with single-channel cryocoolers operating below 30 W input power. This product is currently at a TRL of 6, having been demonstrated in 2024 with several low power cryocoolers.
6. The MCCE-C3EPT design is a higher-power version of the MCCE-C3E with increased power rating, improved ripple filter performance, and inclusion of multi-unit synchronization. This product is currently at a TRL of 6.

The features of the overall MCCE family of electronics are summarized in Table 1.

Table 1. The MCCE-TS family of products

Product:	MCCE-C3E	MCCE-C3EPT	MCCE-TS1	MCCE-TS2	MCCE-HP1	MCCE-HP1+
Drive Configuration	Single	Single	Dual	Dual*	Dual*	Dual*
Max Output Power (W)	30	50	80	80	160	160
Mass Range for 0.1-0.3” Thick Chassis (kg)	0.39 – 0.50	0.56 – 1.2	1.2 – 1.9	1.4 – 2.9	1.7 – 3.0	3.2 – 4.7
Ripple Filter	Passive	Active/ Boost	Passive	Passive	Active/ Boost	Active/ Boost
Comms	RS-422	RS-422	RS-422	RS-422	RS-422	RS-422
Protocol	SLIP	SLIP	SLIP	SLIP	SLIP	SLIP
Vibe Control	No	No	No	3 Harmonics	3 Harmonics	5+ Harmonics
Inrush Limiting	Yes	Yes	Yes	Yes	Yes	Yes
Overcurrent (Output)	No	Yes	No	No	No	No
Clock Sync	No	Yes	No	No	No	No
EEE Parts Min TID (kRad(Si))	30	30	30	30	30	100
TRL	6	6	9	9	5	5
TRL 6 Date	2024	2025	2022	2023	2025 (expected)	TBD

*Configurable as either two identical drives (e.g., dual-opposed motors) or as one high power and one low power drive (e.g., compressor motor plus balancer motor)

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4. Supported cryocoolers

The MCCE architecture is intended to be a universal drive for all Stirling or Pulse-Tube type cryocoolers with either single or dual-opposed sinusoidal linear compressor input. With only minor firmware modifications, most any cryocooler of these families can be operated successfully by the MCCE, provided that the overall power, current, and voltage limits of the MCCE model are observed. Cryocoolers demonstrated to date with MCCE products include:

1. Thales LPT-9510
2. Thales LPT-9310
3. Thales LSF-9997
4. Air Liquide LPTC
5. Sunpower CryoTel DS-1.5, DS-2.1, and DS-Mini
6. Sunpower CryoTel MT, CT and GT
7. AIM SF070
8. AIM SF100
9. AIM MCC030
10. Lockheed Martin Micro1-2
11. Northrop Grumman Microcryocooler
12. Northrop Grumman Mini Cooler Plus (MCP)
13. FLIR FL100

5. CCE production

Creare and WCS have invested in the facilities and people to support the MCCE product line in the near term while continuing to enhance our offerings through additional research and development. Several MCCE models are in production at Creare. Creare's floor space is reconfigurable and currently set-up to assemble, test, and deliver up to 8 CCEs/month. We have a newly added clean space dedicated to CCE programs that is utilized for assembly and integration activities as shown in Figure 1. The area includes bakeout chambers, thermal vacuum chambers, a shaker table and clean assembly and test area that are used for on-site qualification and acceptance testing of cryocoolers, MCCEs or cryocooling system.

We have standardized test protocols for qualification and acceptance tests that can be readily tailored for program-specific environmental requirements. These tests include baseline electrical characterization, random vibration, thermal vacuum/burn-in and final electrical tests. Results from a thermal vacuum testing of a variant of the MCCE-TS1 is shown in Figure 2. Here the power-train efficiency (output power divided by input power less tare power) is measured during warm soak testing at the maximum operational temperature.

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Figure 1. New space CCE integration and test area at Creare. The area is equipped with two thermal vacuum chambers, a shaker table, bakeout chambers, and clean assembly and test benches.

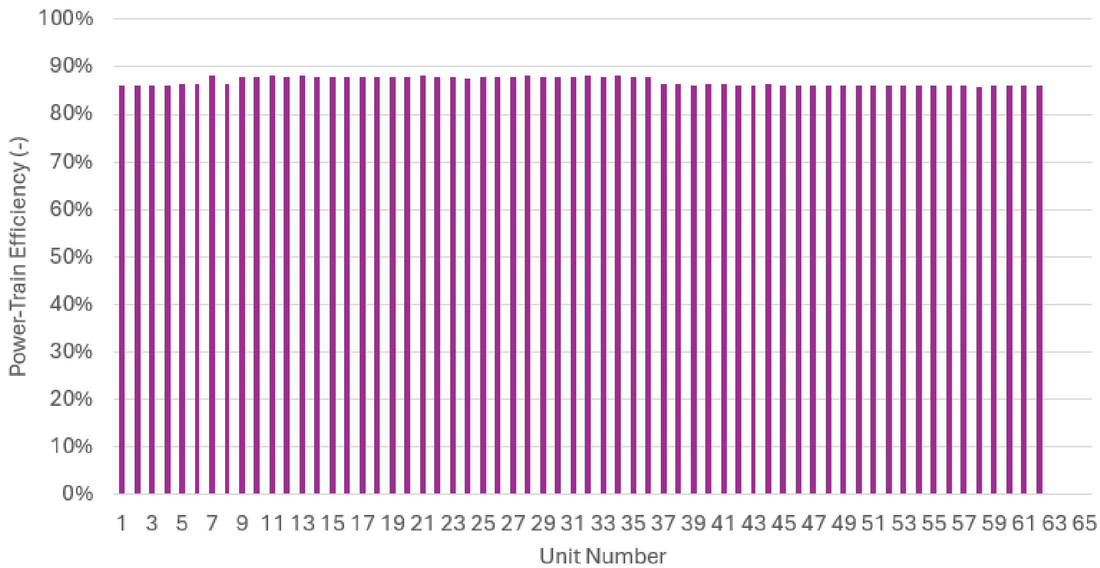

Figure 2. Performance of a variant of the MCCE-TS1 during warm soak testing. There were minor differences in test protocol and CCE configuration for Units 1-8, 9-36 and 37-62, which resulted in slight changes in power-train efficiency.

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6. Emitted vibration testing

In collaboration with Sunpower Inc., Creare and WCS assessed the emitted vibration from a Sunpower CryoTel MT cryocooler with their AVC-GEN2 active balancer (the AVC-GEN2 is an equivalent commercial hardware version of the spaceflight active balancer, the AVC-S). The testing was performed with and without Active Vibration Control (AVC) supplied from an MCCE product. The cryocooler/balancer assembly was mounted on a test fixture, with Kistler 9011A load washers used for emitted vibration feedback to the charge amp within the MCCE. Whereas an accelerometer-based feedback system is inherently dependent on the overall moving mass of the system, the signal generated by load washers is largely consistent regardless of the mechanical system external to the cryocooler/AVC assembly. This version of the MCCE includes vibration control algorithms developed to control the first three harmonics. The test article was mounted on a Newport table at WCS for initial emitted vibration characterization and tuning of the active vibration control algorithms, as shown in Figure 3.

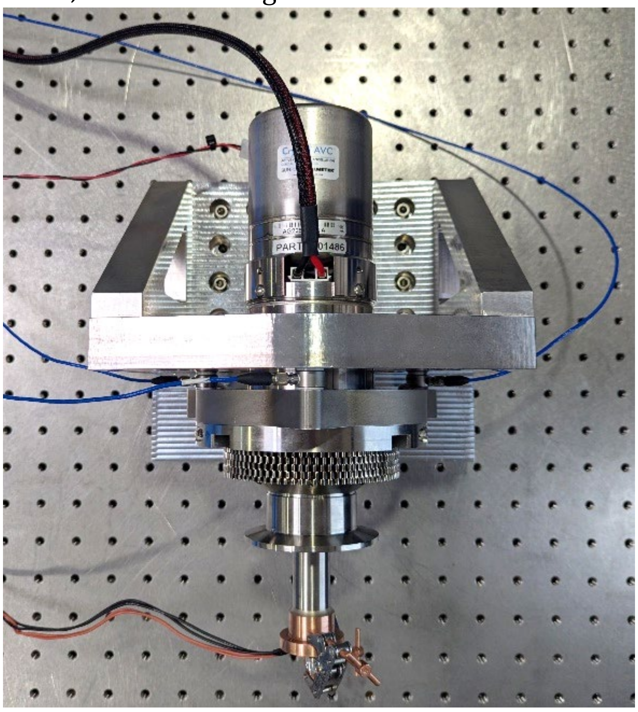

Figure 3. Sunpower CryoTel MT cryocooler and AVC-Gen2 balancer at WCS being prepared for emitted vibration testing with an MCCE product.

As shown in Figure 4, the test article was then mounted on a 6-axis dynamometer at WCS, using Kistler 9067/8C force sensors for emitted vibration measurements. In this setup, the cryocooler cold finger is encapsulated with a sealed bag purged with nitrogen to prevent ice formation, and the cold tip is instrumented with a 1 kΩ PRT for temperature telemetry measured by the MCCE. The dry nitrogen purge allows the cryocooler to achieve sufficiently low cold tip temperatures to deliver up to 80 W to the cryocooler, while avoiding the complications of a vacuum dewar (i.e., vibration effects of stiff tubing routed from a vacuum pump to the test fixture). Prior to operating the cryocooler, testing is performed to ensure the input force from a calibrated impulse hammer accurately translates to reference measurements of the dynamometer. One drive channel of the MCCE is then used to deliver up to a maximum cryocooler power of 80 W while the second drive channel controls the balancer, using the load washers as feedback to minimize

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emitted vibration. The test results with and without active vibration control enabled are shown in Figure 5 for a maximum cryocooler power of 80 W. The results show that the vibration control algorithms were able to reduce vibration at 60 Hz, 120 Hz, and 180 Hz to less than 300 mN rms at each harmonic in the drive axis.

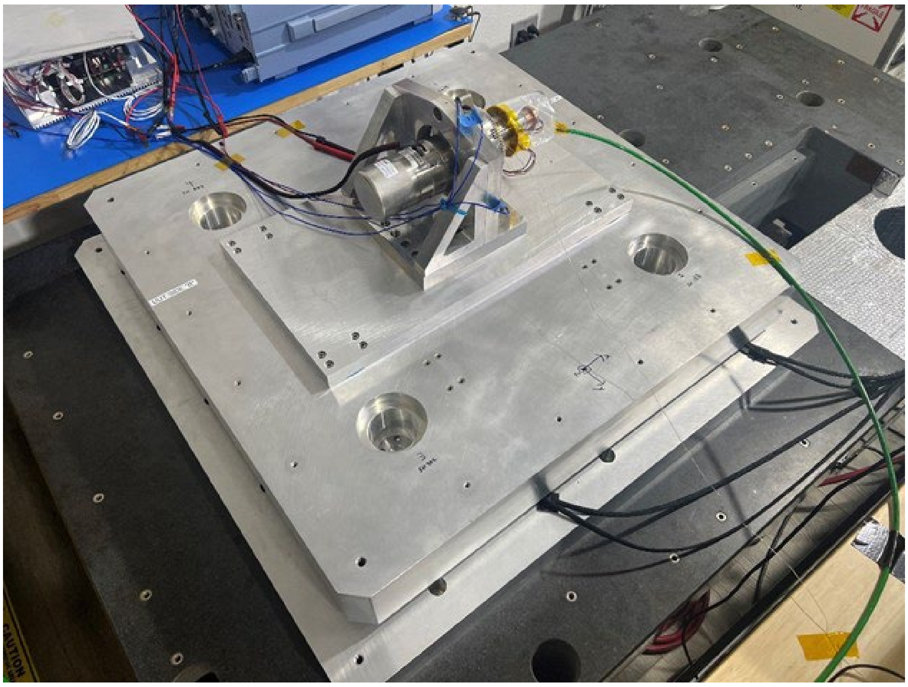

Figure 4. Sunpower CryoTel MT cryocooler and AVC-Gen2 at WCS, configured with dry N2 bag over cold finger and mounted on dynamometer for 6-axis emitted vibration measurements.

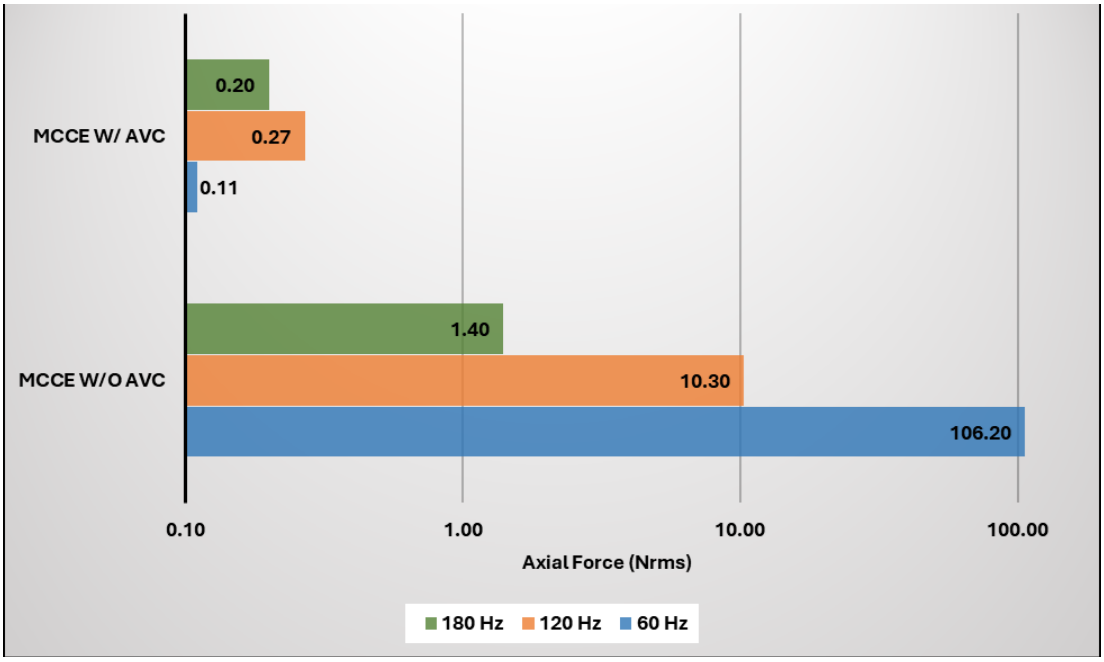

Figure 5. Measured emitted forces from Sunpower CryoTel MT Cryocooler and AVC-Gen2 active balancer with and without active vibration control supplied from a MCCE product. The active vibration control in the MCCE reduced vibrations at the drive frequency by almost 3 orders of magnitude.

7. Conclusion

Creare and West Coast Solutions have matured several models of affordable cryocooler control electronics for a growing space market. The initial unit was developed for low-cost LEO missions and for cryocoolers requiring less than 80 W of input power. Newer models address the lifetime, radiation, power, bus voltage ranges and jitter requirements of a broad range of future space and air-borne missions. Multiple models have achieved a technology readiness level of 9. Recent testing with a Sunpower CryoTel MT cryocooler and AVC-Gen2 active balancer demonstrates the performance of the active vibration control algorithms within the electronics.

Acknowledgments

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