# Characterization Testing of Iris Cryocooler Electronics

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## ABSTRACT

Two versions (100W and 200W) of the Low Cost Control Electronics (LCCE) have been developed by Iris Technology in collaboration with the Jet Propulsion Laboratory (JPL) to provide radiation hardened, high performance, modular, affordable cryocooler electronics. To date, the LCCEs have been used to drive and control a wide range of linear coolers, including the AIM SF100 (pulse tube and Stirling versions), Thales LPT9510, Thales LPT9310, Lockheed Martin Microcryocooler, Northrop Grumman Micro Pulse Tube Cooler, and the Ricor K527. Both of these new LCCEs include input ripple filters to mitigate the current ripple impressed on the input DC power and vibration mitigation to reduce the vibration exported by the cryocooler. This paper describes the performance testing of these LCCE devices, including test results and performance demonstrations of the LCCEs.

## INTRODUCTION

This paper will concentrate on the results of acceptance testing of the LCCE-2. The LCCE-2 is a cryocooler-agnostic set of drive electronics, architected to support both traditional long-life space cryocoolers and tactical cryocoolers, providing the Payload Integrator with a wide range of radiation hard cryocooler system options. The LCCE-2 is modular, scalable, affordable, and provides the critical cryocooler operational functionality that fully envelopes the needs of a typical space mission (high efficiency motor drive, closed loop temperature control, input ripple filter, and vibration control). This design has been matured culminating in a flight-design Engineering Model immediately applicable for a wide range of missions. The LCCE products are also suitable for the control of other systems such as actuators, motors and heaters that require a controlled power drive.

The LCCE-2 specifically includes two enhancements that had not been part of previous LCCE efforts. These enhancements are an input ripple filter (IRF) to reduce the current ripple imparted onto the input power bus and a vibration control algorithm that is used to reduce the vibration produced by the compressor that could adversely affect overall system performance.

The LCCE-2 acceptance testing was performed with both a resistive load and a Thales LPT9510 cryocooler. Cryocooler vibration was measured with an Endevco 7703A-1000 accelerometer.

*Cryocoolers 19,* edited by S.D. Miller and R.G. Ross, Jr.

**Table 1.** Summary of Critical Requirements from LCCE-2 Performance Specification.

| Parameter | Characteristic |
|---|---|
| **Operating Input Voltage** | 22 to 35 VDC |
| **Number of Motor Drives** | 2 independent motor drive outputs (each rated at > 50W) |
| **Total Output Power** | Continuous operation at 100 WAC and 28 VDC input voltage. |
| **Efficiency** | > 85%, with output power at 100 WAC and input voltage at 28 VDC. |
| **Tare Power** | < 2.2 W @28 VDC |
| **Output Voltage Sinusoidal Symmetry** | < 3% THD including harmonics up to 5 kHz, above 20 watts output power. |
| **Operating Frequency** | Control Output drive frequency shall be adjustable from 40 to 150 Hz with 0.1 Hz resolution. |
| **Vibration Measurement** | Measure cryocooler vibration at the fundamental (Fc), second harmonic (2 x Fc) and third harmonic (3 x Fc) of the drive frequency. |
| **Input Current Ripple** | < 200 mA peak-to-peak @ 100W output and 28 VDC input |
| **Inrush Current** | After application of +28V power the initial inrush (charging) current due to distributed capacitance, EMI filters, etc., shall be completed in 30 μs with its peak no greater than 25 Amps. |
| | The rate of change of inrush current after the initial application of +28V power shall not exceed 50 mA/μs. |
| | Steady state operation shall be attained within 100 ms from turn-on or the start operating mode change, except for motors. |
| **Vibration Control** | Measure cryocooler vibration at the fundamental (Fc), second harmonic (2 x Fc) and third harmonic (3 x Fc) of the drive frequency. |
| | Provide closed loop vibration control based on measured cryocooler vibration. |
| **Temperature Sensor Set-point** | Adjustable between 60K and 300K when using a Cernox CX-1080 sensor. |
| **Temperature Sensor Sensitivity** | < 0.1K (TBR) at 70K when using a Cernox CX-1080. |

## OVERVIEW OF LCCE-2 REQUIREMENTS

The detailed requirements for the LCCE-2 are given in Reference 1, and a summary of the critical performance criteria is provided in Table 1.

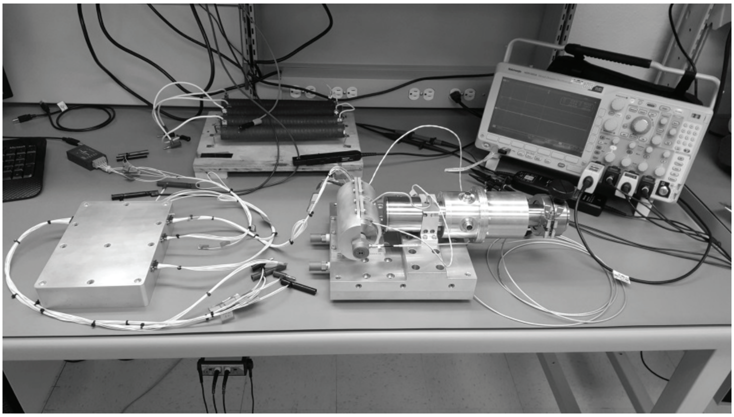

**Figure 1**. LCCE-2 Performance Qualification Test Setup.

## LCCE-2 TESTING

LCCE-2 testing followed a standard build up. First circuit boards were tested stand-alone to validate performance prior to assembly into an enclosure. The assembled system was then subjected to more engineering tests to validate performance until it was determined to be ready for acceptance and qualification testing. The results presented in this paper have been excerpted from acceptance and qualification test results. Figure 1 shows the test setup for performance qualification testing.

## LCCE-2 TEST RESULTS

The following paragraphs present the results of selected portions of the acceptance and qualification test results. Only tests with data that provide general interest or specific differentiation are presented herein.

### Tare Power Test

The Tare Power test was performed at three voltages (22V, 28V, and 35V) under three conditions (Disabled, No Telemetry, and Telemetry ON). The results are shown in Table 2. When the LCCE-2 is "Disabled" the PWM controller is disable so none of the auxiliary voltages are produced, basically only the Input Ripple Filter is active. When the LCCE-2 is in the "No Telemetry" mode, all the voltages are present, but there is no communication and no activity in the CCE. When the LCCE-2 is in the "Telemetry ON" mode the CCE is inactive, but a telemetry message is being requested and sent every 500 ms. Note that the LCCE-2 is under the 2.2W requirement at 28V.

### Input Voltage Range Test

The LCCE-2 was operated at three input voltage levels, 22V, 28V, and 35V. At each voltage power level, the LCCE-2 was programmed to output 110W into a resistive load. The output waveform was checked for sinusoidal characteristics and channel balance. This test was successful at all three input voltage levels.

### Output Voltage Range Test

The peak output voltage is adjustable in 15.928mV steps from 0 to in excess of 22V. For the Output Voltage Range Test the LCCE-2 was operated at the worst case input voltage level of 22V. The LCCE-2 produced output waveforms at 5V (6.25W), 10V (25W), 15V (56.25W) and 20V (100W) into a resistive load. Each of the output waveforms was checked for sinusoidal characteristics and channel balance. This test was successful at all four output power levels.

### Voltage Ramp Rate Test

The Voltage Ramp Rate Control is designed to provide an upper limit on the ramp rate of

**Table 2**. Results of Tare Power Testing at 22V, 28V and 35V.

| Voltage | Condition | Input Current (Amps) | Input Power (Watts) |
|---|---|---|---|
| 22 | Telemetry ON | 92mA (max) | 2.02W (max) |
| 22 | No Telemetry | 92mA (max) | 2.02W (max) |
| 22 | Disabled | 8.3mA (max) | 0.183W (max) |
| 28 | Telemetry ON | 78mA (max) | 2.18W (max) |
| 28 | No Telemetry | 78mA (max) | 2.18W (max) |
| 28 | Disabled | 9.7mA (max) | 0.272W (max) |
| 35 | Telemetry ON | 69mA (max) | 2.42W (max) |
| 35 | No Telemetry | 69mA (max) | 2.42W (max) |
| 35 | Disabled | 11.4mA (max) | 0.399W (max) |

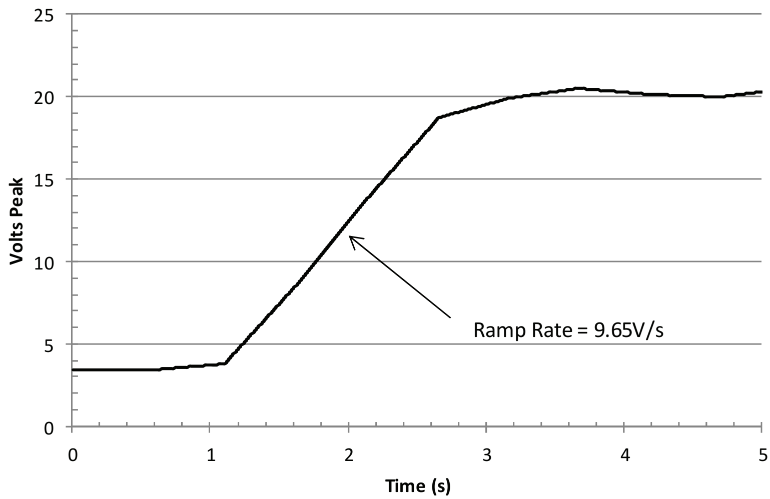


**Figure 2**. Ramp Rate Test Results

the peak voltage of the waveform during a single step of the of controller operation. Thus, no matter what value is set, that value cannot be exceeded. For this test the operator set the ramp rate to 10V/s. The nearest achievable ramp rate was 9.88V/s. The ramp rate is selectable in multiples of 0.309V/s. Since the Ramp Rate Control establishes an instantaneous limit for the ramp rate, the measured ramp rate will be less than the selected ramp rate. For this test the measure ramp rate was 9.65V/s, as shown in Figure 2.

**Operating Frequency Test**

The LCCE-2 is required to provide frequency adjustment from 40Hz to 150Hz with 0.1Hz resolution, as shown in Table 1. The LCCE-2 is designed to provide frequency steps of about 0.0013Hz steps from 24Hz to 240Hz. For this test the LCCE-2 requirement was verified. Waveforms were generated and verified for frequency accuracy for 40Hz, 44.9Hz, 45Hz, and 150Hz.

**Output Efficiency Test**

The LCCE-2 is required to provide 85% efficiency with output power at 100 WAC and input voltage at 28 VDC, as shown in Table 1. For this test the LCCE-2 efficiency was measured for 0W to 100W of output power at three different input voltage levels, 22V, 28V, and 35V. The test showed that at 22V input an efficiency of 83.9% was achieved, at 28V input an efficiency of 85.4% was achieved, and at 35V input an efficiency of 86.7% was achieved. The sweep results for the 28V input test are shown in Figure 3.

**Reflected Ripple Current Test**

The LCCE-2 is required to impart an input ripple current of less than 200 mA peak-to-peak when the LCCE-2 is providing 100W output power with an input voltage of 28 VDC. To test this requirement Iris commanded the LCCE-2 to provide 110W into a resistive load and measured the input ripple current on an oscilloscope. The resultant waveform measure 194 mA peak-to-peak and is shown in Figure 4.

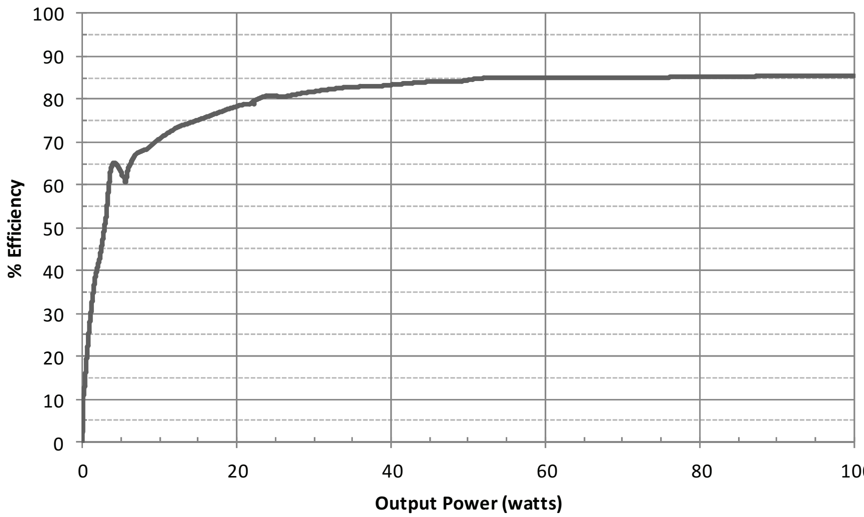


**Figure 3**. LCCE-2 Efficiency with 28V Input Power.

### Inrush Current Test

The LCCE-2 requirement for inrush current has three parts; (1) after application of 28V power the initial inrush (charging) current due to distributed capacitance, EMI filters, etc., shall be completed in 30 µs with its peak no greater than 25 Amps, (2) the rate of change of inrush current after the initial application of +28V power shall not exceed 50 mA/µs, and (3) steady state operation shall be attained within 100 ms from turn-on or the start operating mode change, except for motors. The LCCE-2 was monitored with an oscilloscope during the initial application of power. As shown in Figure 5, for the first requirement, the initial inrush peak was 4.36A less than the 25A limit and was completed in 4.9µs, less than the 30µs limit. For the

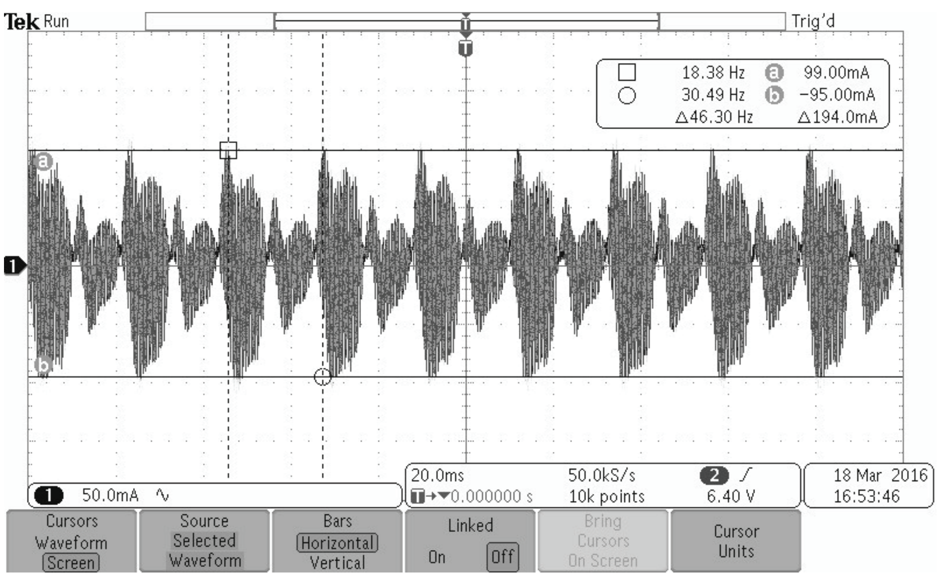


**Figure 4**. LCCE-2 Current Ripple Test Results.

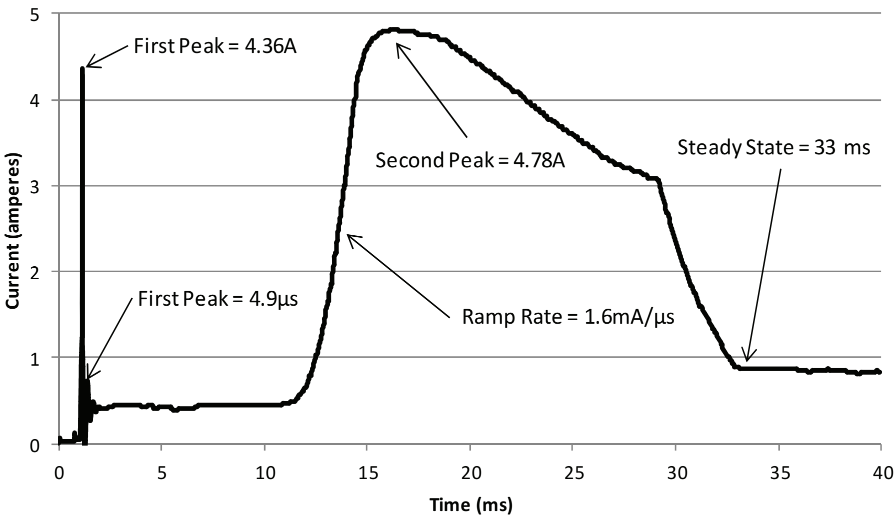


**Figure 5**. LCCE-2 Inrush Current Test Results.

second requirements, the ramp rate of the inrush current was 1.6 mA/µs less than the 50 mA/µs limit. For the third requirement, steady state current was achieved in 33 ms, less than the 100 ms limit.

## Vibration Algorithm Test

The LCCE-2 requirement for vibration is twofold, the first requirement is to measure the cryocooler vibration at the fundamental (Fc), second harmonic (2 x Fc) and third harmonic (3 x Fc) of the drive frequency, and the second is to provide closed loop vibration control based on measured cryocooler vibration. To test these requirements, the LCCE-2 was setup to drive a Thales LPT9510 cooler in a fixture with an Endevco 7703A-1000. The LCCE-2 actually measures five harmonics so the first requirement is met, and testing showed that the five harmonic algorithm reduced the vibration measured by the LCCE-2. These results are illustrated in Figure 6. In Figure 6 time runs from left to right, and the vertical axis is non-dimensional vibration counts. When the graph in Figure 6 first starts there is no vibration as the compressor

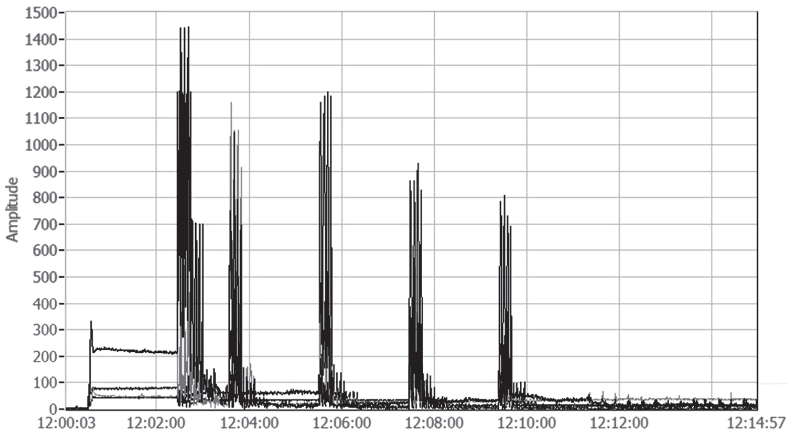


**Figure 6**. LCCE-2 Vibration Algorithm Test Results.

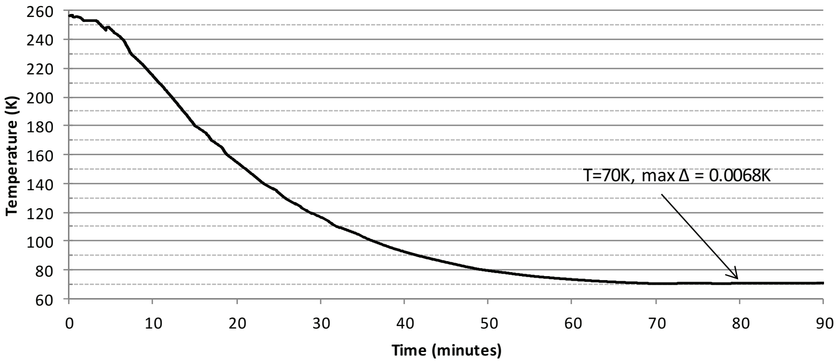


**Figure 7**. LCCE-2 Temperature Sensitivity Test Results.

is not on. When the compressor is turned on, we see that the vibration levels increase rapidly. The highest vibration at turn-on is the fundamental frequency, then the third harmonic, the second, fourth and fifth harmonics are all about the same at this time. As the algorithm is run, vibration extremes are seen as the algorithm adjusts the phase and amplitude of the output waveform. We can see five distinct areas, each corresponding to the five harmonics. When the algorithm is complete, we see that all of the harmonic vibrations have been reduced, and only the second harmonic has not been reduced to levels near the off conditions.

## Temperature Control Test

The LCCE-2 requirements for temperature are twofold; (1) the temperature set-point is adjustable between 60K and 300K when using a Cernox CX-1080 sensor, and (2) temperature sensitivity is less than 0.1K at 70K when using a Cernox CX-1080. The first requirement was demonstrated by showing that the LCCE-2 could be adjusted to 60K and 300K. The second requirement was demonstrated with a Thales LPT9510 cooler with a Cernox-1080 sensor on the cold tip. The temperature set-point was set to 70K, and the system was allowed to cool. The system settled with a maximum deviation of 0.0068 K, much less than 0.1 K. This is illustrated in Figure 7. In addition to the tests to verify the requirements, a test was run to demonstrate system performance with a heat load. The system was run to 120 K, stabilized, and then a heat load of 0.25W was added and the system response was measured. The system settled at 120 K with a maximum deviation of 0.0055 K. This is shown in the left-hand graph in Figure 8. A heat load of 0.25 W was added, and again the system settled at 120 K with a maximum deviation of 0.0055 K; this is shown in the right-hand graph in Figure 8.

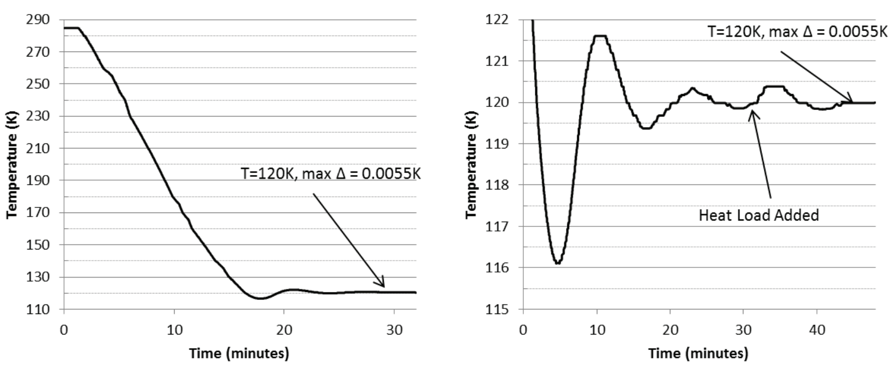


**Figure 8**. LCCE-2 Heat Load Test Results.

## CONCLUSIONS

The Second Generation Low Cost Control Electronics (LCCE-2) and the High-Power Low Cost Control Electronics (HP-LCCE) were both successful in demonstrating the enhanced features of the LCCE product line while maintaining previous performance baselines. Some of these enhancements are listed below.

- Incorporation of an Input Ripple Filter protects the host power bus from current surges imparted when creating a cryocooler waveform, and allows the LCCE-2 and HP-LCCE to work with lower impedance cryocoolers that have higher peak voltage requirements.
- Incorporation of a firmware-only algorithm that compensates for the voltage ripple at the output of the IRF, thus reducing the total harmonic distortion in the cryocooler power waveform.
- Incorporation of the Vibration Mitigation Algorithm that reduces the vibration imparted to the structure of the spacecraft by modifying the power waveform to the cryocooler. This algorithm requires that an accelerometer be attached to the cryocooler to allow the LCCE-2 and HP-LCCE to determine the vibration components.

In conclusion, the LCCE 2 and HP-LCCE were successful in establishing and delivering a low cost, radiation hard, high performance, general purpose control electronics module to support future space missions.

## REFERENCES

1. *Second Generation Low Cost Cryocooler Electronics (LCCE-2) Performance Specification*, Revision A, Iris Document Number SYS10005, dated October 22, 2015.