Universal Drive for Tactical Cryocoolers

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ABSTRACT

Superconducting Electronics (SCE) systems are becoming commonplace due to their substantial benefits in performance and cost when compared to traditional, semiconductor-based components. For example, HYPRES, Inc. is presently developing novel superconducting digital-RF technologies that enable highly efficient multi-carrier, broadband systems for military and commercial communications and other RF applications. To achieve widespread adoption of SCE systems, low-cost and rugged cryocoolers and associated drives are needed. In cooperation with HYPRES, Creare is developing a universal Tactical Cryocooler Drive (TCD) for Stirling and Pulse tube-class cryocoolers. TCD provides dual independent drives that can be customized for each application with software changes. In this paper the results of a comprehensive design study and brassboard demonstration are described. The electronics simultaneously and independently controls dual cryocooler compressors with input power up to 270 W and efficiencies as high as 96%. The technology is scalable to power levels of 1,500 W per channel. The electronics has been demonstrated the following attributes through brassboard tests: (1) a Pulse Width Modulation (PWM) control strategy, which results in minimal ripple currents, (2) a custom, programmable waveform generation method based on a Graphical User Interface (GUI), (3) thermal control was able to maintain temperature at 66 K in the presence of thermal loads up to 2.5 W, and (4) a control strategy that minimizes the exported vibration from the dual-compressor apparatus by independently controlling drive amplitude and phase relationships. This paper describes the results of these demonstrations and our plans for building and demonstrating a prototype with the form, fit, and function of the final product.

INTRODUCTION

Several notable aerospace manufacturers have adapted their space cryocoolers for tactical applications, such as the cooling of SCE devices, while other manufacturers exclusively focus on terrestrial applications.[1,2,3,4] These manufacturers have developed proprietary machine designs and have incorporated unique thermal and vibration control algorithms to achieve optimal cryocooler performance for specific applications. Reasons for doing so include: differing cooling and lifetime requirements, differing needs to achieve low exported-vibration levels, and compensation for individual cryocooler idiosyncrasies. The tradition for minimizing exported vibration from linear compressors is via machine design, by using a pair of opposed compressors with their piston driven by a common current and, therefore, reciprocating in opposite directions. Although this simple approach reduces much of the vibration, residual vibration is caused by asymmetrical characteristics such as wear, friction, seals, etc. As a result, many cryocoolers now include force, acceleration, or displacement sensors and unique control algorithms to minimize exported vibration levels. Yet

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other cryocooler manufacturers have also looked at sensorless control to accomplish some of the same goals without the need for additional sensors.

With such a wide range of potential cryocooler characteristics, it becomes advantageous to develop a universal drive that is capable of meeting differing manufacturer needs, without requiring custom hardware development for each. This will achieve dramatic reductions in development cost, schedule, and risk. SCE systems are becoming more common due to their substantial benefits in performance when compared to traditional, semiconductor-based components. For example, HYPRES is presently developing novel superconducting digital-RF technologies that enable highly efficient, multi-carrier, broadband systems for military and commercial communications and other RF applications.[5,6,7] Tactical cryocoolers are required for SCE systems to supply the cooling necessary to operate the High Temperature Superconducting (HTS) devices. To support the widespread adoption of SCE systems, Creare is developing a universal TCD that can provide a common interface between SCE system level functions and a range of single phase, linear motor-type cryocoolers and vendors with minimal cost and technical risk. This paper describes the results of these demonstrations and our plans for building and demonstrating a prototype with the form, fit, and function of the final product using a four-stage, pulse tube cooler.

APPROACH

Our design study was highly successful in demonstrating the feasibility of our approach. During this effort, the following attributes were implemented (1) a custom, programmable waveform generation method, and a GUI to satisfy this range of needs, (2) a hardware topology that was able to simultaneously and independently drive dual-cryocooler compressors with input power as high as 270 W and efficiencies as high as 96%, (3) a PWM control strategy, which results in minimal ripple currents, (4) a design path, which will enable power levels up to 1,500 W per channel, (5) thermal control able to maintain cryogenic temperatures in the presence of thermal loads as high as 2.5 W, (6) minimizing the exported vibration from the dual-compressor apparatus by independently controlling drive amplitude and phase relationships, and (7) several packaging concepts which can be pursued during the following phases, including completely enclosed packaging, and two open frame approaches that rely on either forced-air convection or baseplate conductive cooling.

During follow-on development, the following is planned: (1) optimize the design including electrical, software, and mechanical details, (2) extend the PWM algorithms for closed-loop, shutdown, and stroke-based control algorithms, as well as a variety of monitoring and protection features, (3) fabricate and test a fully functional laboratory grade prototype, and (4) test it with an SCE cryogenic cooling system in coordination with HYPRES.

TCD DESIGN

Overview

Our concept is illustrated in Figure 1. The primary subsystems include: (1) dual, independent motor control circuits that can drive one or two compressors at up to 1,500 W, and (2) a software configurable Central Processing Unit (CPU) that supports unique cryocooler control algorithms. PWM-based drive circuits ensure maximum efficiency, small size, and simplified thermal packaging. While many cryocooler manufacturers have developed unique control algorithms to minimize temperature fluctuations and exported vibration level, their approaches and implementations vary. To support this wide range of requirements, our universal TCD can accept thermal feedback signals; acceleration, force, or displacement transducer inputs for vibration and stroke control, and unique control algorithms for deriving individual motor excitation waveforms. Waveform functions can be programmed by the user, stored within the TCD nonvolatile memory, and generated in real time by the CPU. In this way, unique cryocooler needs can be accommodated through software changes only, and no custom hardware development or modifications are necessary. It is also possible to provide information to the user regarding cryocooler and/or controller health status and performance. For example, the user can be warned about compressor overheating, worn bearings,

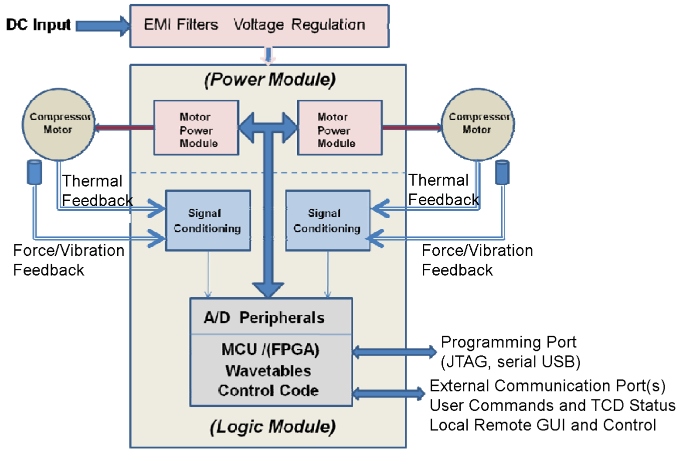


Figure 1. Conceptual block diagram of the TCD.

or a piston which requires excessive drive power. This information can be presented through a standard display, continuous operational data available via a standard interface bus, and/or simple alarms. This information can be provided locally at the TCD or communicated to system operators at existing control panels.

During the design study, the TCD operational and environmental requirements were defined by: (1) considering the features required for a range of SCE cryocoolers, including defining a range of frequency, amplitude, phasing, and thermal and vibration control algorithm requirements, and (2) defining environmental requirements, including thermal, vibration, and EMI needs. Table 1 shows two sets of requirements: (1) the requirements for the prototype demonstration to be conducted during follow-on development, and (2) requirements for a sub-scale design phase prototype.

Electronics Hardware

Design. The concept illustrated in Figure 1 is used and the requirements shown in Table 1 to design the electronics hardware that supports the PWM control software residing within the TCD. The Phase I TCD electronics hardware prototype consists of two separate electronic assemblies: the Digital Signal Processor (DSP) controller; and the power control module. An off-the-shelf DSP module was used for cost and schedule reasons. It is based on a Texas Instruments DSP, which is specifically designed for highly integrated motor control applications. It also has a direct military certified replacement, and a similar, fully qualified substitute is also available for space applications.

Table 1. TCD specifications to support design phase demonstration and long-term objectives.

	Design Phase Demonstration Goal	Long Term Demonstration Goal
Frequency	1–100 Hz, Typically 30–60 Hz	1–100 Hz, Typically 30–60 Hz
Output	200–300 W, Two Independent Channels, Single Phase	0–1,500 W, Dual, Independent, Single Phase
Input Power	28 VDC	TBD
Programmability	Waveshape, Frequency, Amplitude, Phase	Waveshape, Frequency, Amplitude, Phase
Thermal Control	Manual	± 0.01 K
Vibration Control	Manual	± TBD G
Environmental	N/A	MIL-STD-810
Shock and Vibration	N/A	MIL-STD-810
EMI	N/A	TBD
Cost	N/A	< $300

The power module assembly includes two identical channels (each capable of up to 1,500 W), current monitoring (for circuit protection and/or detecting deteriorating compressor conditions), temperature monitoring (both for temperature control of the cold head as well as for monitoring operation of the compressor itself), and vibration monitoring (to implement vibration minimization algorithms). The power module packaging was designed to minimize size, weight, and cost, while ensuring adequate thermal management.

Fabrication. A prototype was fabricated based on this design, including design of the Printed Circuit Board (PCB) assemblies, selection and layout of the components, specification of the traces on the circuit board, procurement, fabrication, and testing. A photograph of the completed design phase prototype is shown in Figure 2. There are three subassemblies: the DSP controller module (bottom), the power control module (middle), and the heat sink assembly (top). Each of the two heat sink assemblies has been designed to remove up to 40 W. The power module consists of two H-bridge modules, connectors to provide attachment to the DSP module, and various signal conditioning electronics to accommodate the feedback and control signals.

It is worth noting that this approach also shows the flexibility of our approach, where it may be possible to integrate our standard controller with various power modules having different specifications such as number of phases, voltage, current, or power ratings.

Software

In this subtask, the control software that resides within the TCD to create a PWM approximation of any arbitrary waveform was developed. This section provides an overview of our approach and describes work performed to implement this technique on our DSP platform. The following parameters are required to define a PWM signal:

- Clock frequency (h). This determines the maximum clock resolution of the PWM.
- PWM period (p). This is defined as the time between two successive rising edges of the PWM output, assuming the output is active high.
- Duty cycle (x). This is the fraction of the period for which the output is high.

The waveform is defined by:

- Sample rate (fs). This is the frequency at which the waveform is discretized.
- Wave period (T). This is the time required for the waveform to repeat itself.

The approach for forming the PWM approximation is known as the intersective method. Consider a counter with increments from zero to p * h in time, *p*, and then resets to zero. For each such counter interval, a value, *y*, of the waveform corresponding to that interval is sampled. The value *y* should lie within the range $0 \le y \le p*h$. If the PWM output is set to "high" when the counter is less than or equal to *y* and "low" when the counter exceeds *y*, a signal will be formed whose integral will

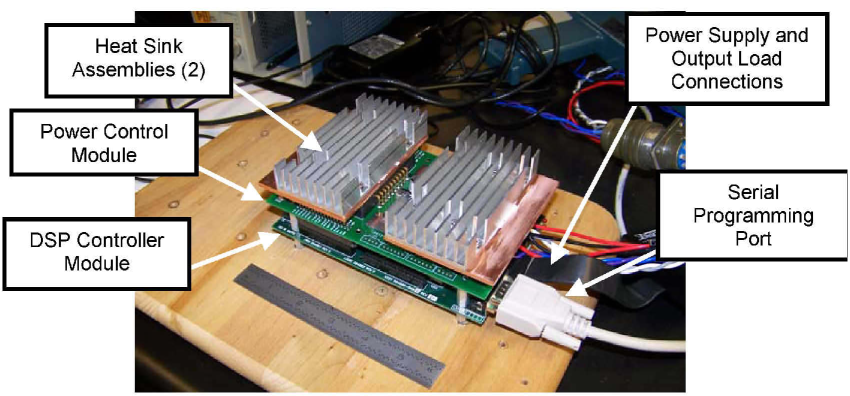


Figure 2. Completed TCD prototype used for Phase I testing.

approximate the integral of the original waveform. Thus, the duty cycle of the PWM whose cycle begins at time, i, will be:

$$x(t) = \frac{t_i}{hp} \tag{1}$$

where t_i is the time of intersection, relative to the start of the period:

$$t_i = \frac{y(t)p}{hp - (y(t+p) - y(t))} \tag{2}$$

After developing this algorithm, it was implemented in the C-based programming language for the Texas Instruments DSP. Figure 3 shows the output of the PWM module as it simulates a 60 Hz sine wave with a mean value of 1.65 volts and a peak-to-peak magnitude of 3.3 V. The mean value of the PWM waveform is also 1.65 V in this case. At instances when the magnitude of the sinusoid is large (near 3 V for example at t = 2 mS and 8 mS), the duty cycle and thus average value of the PWM waveform is relatively high; and at low magnitudes (near 0 V at t = 4 mS and 12 mS), the duty cycle is relatively low.

Graphical User Interface

A Windows-based GUI was developed to allow the user to control the TCD. Figure 4 shows a screen capture of the actual GUI. Using this interface, the user can send amplitude, frequency, phase (relative phase between the two compressor control signals), and temperature control values to the DSP. The user can also optionally poll each compressor for the following data values: vibration force, temperature, power, and health status (a simple good (green), warning (yellow), error (red) indicator of the compressor's status). When the *Poll for compressor data* checkbox is selected, the GUI will automatically request these data values from the DSP controller at approximately 0.5 Hz over a standard serial communication link.

Control value updates, as well as requests for updated compressor data values, are sent over a serial link between the Windows PC and the DSP controller board. A serial command packet protocol has been developed for this communication. The serial packet protocol includes a start byte and a serial frame. The serial frame is composed of a payload length, a payload (made up of the command and appropriate command parameters), and a payload checksum.

EXPERIMENTAL PERFORMANCE

The TCD prototype was developed, first with a lumped Resistance-Inductance (RL) load, then with a single SunPower CryoTel CT cryocooler, and finally, in a dual, opposed piston setup to

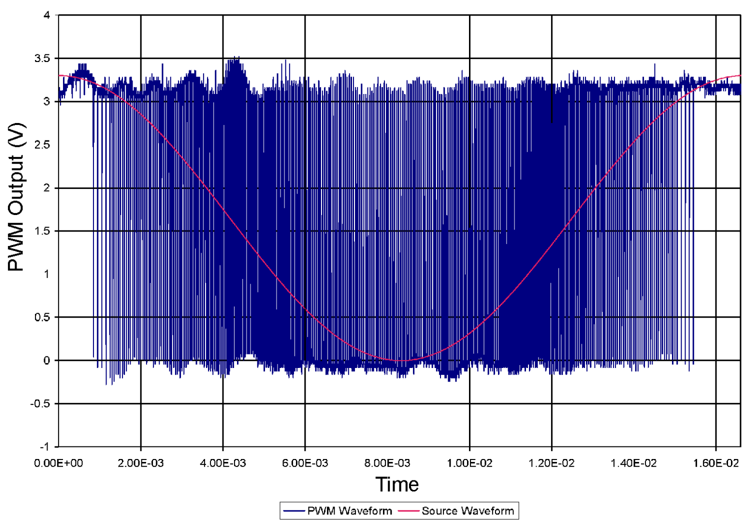


Figure 3. PWM and Source Waveforms for the DSP-based TCD.

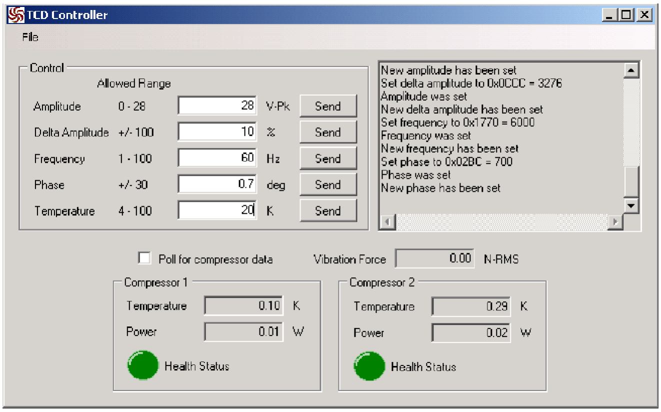


Figure 4. The TCD controller GUI.

demonstrate thermal control in a vacuum vessel as well as vibration reduction.

The lumped RL load testing and single compressor testing are omitted for brevity, with a focus on the dual opposed piston testing. During this dual piston testing, we: (1) characterized the cryocooler compressor motors and the TCD output waveforms; (2) evaluated the TCD in providing thermal control of a cryocooler cold head in the presence of thermal loading; and (3) demonstrated vibration reduction by independently varying the amplitude and phase relationships of the dual compressor drive.

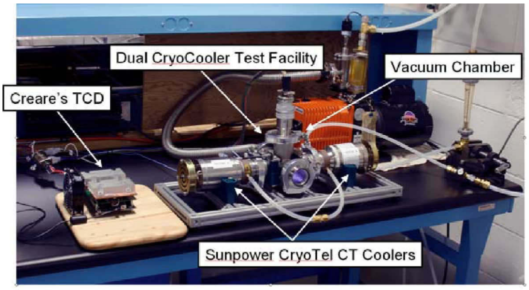
Dual Compressor Testing

To evaluate both TCD channels simultaneously in a realistic thermal vacuum environment, a vacuum test facility was fabricated for the dual cryocooler testing. Both cryocoolers were assembled such that they were coupled into the same vacuum space, where thermal regulation test using a small thermal load was implemented. The cryocoolers was mounted in such a way to allow an open-loop vibration reduction test and evaluation. Two photographs of the facility are shown in Figure 5. The top photograph shows the entire facility, including Creare's TCD prototype, two (2) SunPower CryoTel CT coolers, and the vacuum chamber. The bottom photograph shows the internal vacuum chamber components through a viewing port. Within the vacuum chamber are the two cryocooler cold heads, each having a thin-film heater to simulate independent thermal loads, two temperature sensors, and a low-power Light Emitting Diode (LED) to illuminate the chamber for viewing purposes.

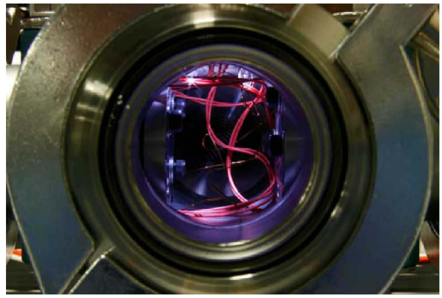
Several tests were conducted of the dual channel TCD using this facility. First, the TCD output current and voltage waveforms was examined to ensure that the drive was working properly. Typical waveforms are shown in Figure 6. In this case, since the thermal loads were relatively low (< 3 W), the drive amplitude required to achieve cryogenic temperatures was modest. For the particular test shown in Figure 5 and Figure 6, the drive output amplitudes are approximately 9 A peak and 9 V peak, or roughly 6.3 A RMS and 6.3 VRMS. The power level shown was roughly 40 W input power to each compressor.

Figure 7 shows the cold head temperature as a function of drive voltage. The plot shows temperatures as low as 50 K; temperatures as low as 38 K were achieved. Figure 8 shows the TCD electrical efficiency over a range of output power (compressor input power). As expected, the efficiency is relatively low at low output powers (40% at 5 W out), although the efficiency increases sharply as the output power increases (88% at 75 W). Creare previously achieved efficiency as high as 96% at an output power of 111 W using the lumped R-L load.

Figure 9 and Figure 10 show the most important integrated performance data. Figure 9 shows the ability of the TCD to regulate the cold head temperature at a constant temperature in the presence of a varying thermal load by varying the output drive voltage. Without any appreciable thermal load, a compressor input drive voltage of roughly 11 V RMS resulted in a cold head tempera-



(a)



(b)

Figure 5. (a) Two cryocoolers with coupled thermal and vibration environments, (b) A viewing port allows inspection of the cold heads during the test.

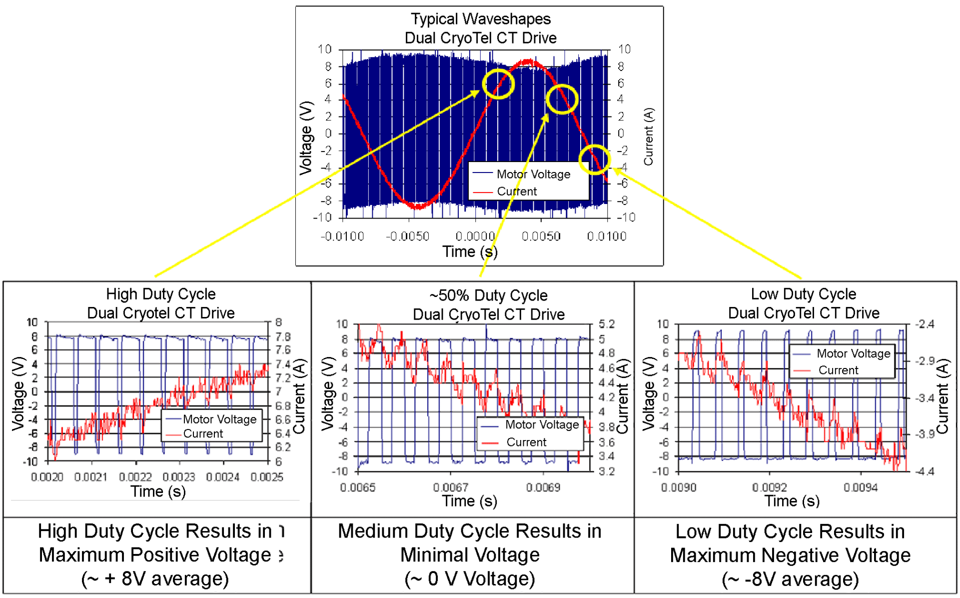
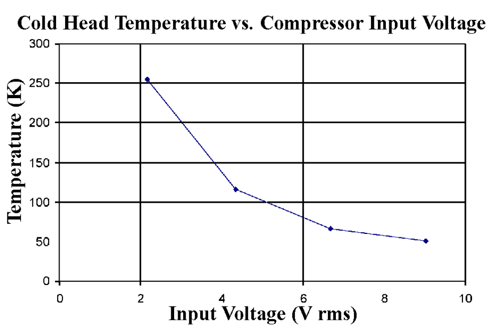


Figure 6. Typical waveshapes for the dual compressor test.



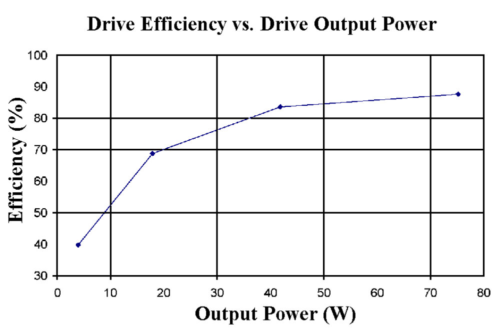


Figure 7. Cold head temperature vs. compressor

Figure 8. Drive efficiency vs. drive output power. input voltage.

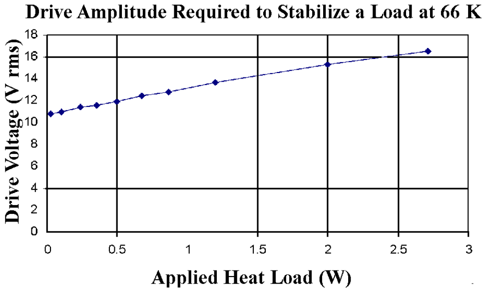


Figure 9. Drive output voltage amplitude required to stabilize a thermal load.

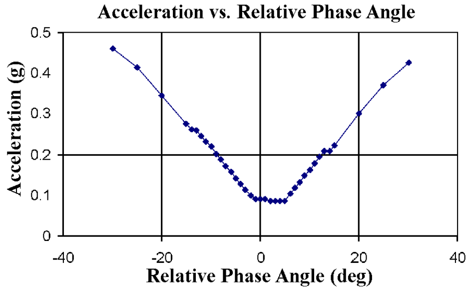


Figure 10. Reducing acceleration by varying the relative phase angle between the two drive outputs.

ture of 66 K. As the thermal load increased, the compressor drive voltage magnitude was varied to maintain the cold head temperature at 66 K. With a thermal load of 2.7 W, the unit was able to maintain 66 K with a compressor drive voltage magnitude of 16.5 V RMS. This test clearly shows the ability of the TCD to control the cold head thermal set point by independently controlling the individual output voltage magnitudes.

Figure 10 shows the ability of the TCD to minimize vibration of the apparatus, as determined using an accelerometer attached to the mounting frame between the two coolers. We first set the relative phase angle to 0° and adjusted the individual drive voltage magnitudes to minimize the observed vibration. We then adjusted the relative phase angle ± 30° and recorded the observed acceleration. The minimum acceleration was approximately 0.09 g near 0°, and increased to approximately 0.45 g at ± 30°. We also observed that the midpoint of the vibration characteristic was not precisely at 0°, but rather offset by approximately 3°. This test clearly shows the ability of the TCD to minimize vibration by independently controlling the individual output voltage magnitudes and relative phase angle.

FUTURE WORK

The described work clearly shows the feasibility and applicability of the proposed approach, although more work must be done to achieve all the functionality desired and to prove the TCD with SCE cryogenic systems in actual practice. The necessary outcome of the next phase of development is a form, fit, and function TCD demonstration which will be validated with laboratory tests in coordination with the HYPRES SCE system. This objective will achieve by expanding upon the prototype hardware and software to provide a refined design and demonstrable TCD system which meets the specific operating requirements of an existing cryogenic cooling system. Our near-term target application is the developmental superconducting RF transceiver SCE assembly being developed at HYPRES. The follow-on TCD unit will be built to specifically meet the requirements set by the dual set of linear compressors located at HYPRES. We will design, build, and test an enhanced TCD featuring new automatic control modes for regulating temperature and for providing start-up and protection functions required for reliable operation of the SCE electronics. Automated controls will not only provide fault protection, but will also remove labor intensive manual operations required for start-up and shutdown sequences. The automation, user interfaces, and system interfaces of the follow-on system will additionally provide for logging of both operational data and fault status and could potentially be interfaced with a data network to provide condition-based maintenance diagnostics. We intend to deliver a dense TCD package that will replace the entire rack of electronic equipment and linear power amplifiers presently used to drive and control the compressors at HYPRES. The ultimate goal is to provide a platform and a package which can be migrated to SCE products suitable for production and delivery for DoD applications.

CONCLUSIONS

A prototype universal TCD for Stirling and Pulse tube-class cryocoolers has been demonstrated. Our TCD provides dual, independent drives, which can be customized for each application with only software changes. Test results show that the TCD can simultaneously and independently control dual cryocooler compressors with input power up to 270 W and efficiencies as high as 96%. Further, the TCD design is scalable up to power levels of 1,500 W per channel. We demonstrated a control strategy with minimal ripple currents; thermal regulation that maintains cold head temperature at 66 K in the presence of thermal loads up to 2.5 W; and minimization of exported vibration by independently controlling drive amplitude and phase relationships.

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