Developments in Advanced Cooler Drive Electronics

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ABSTRACT

An overview is given of the cooler drive electronics capabilities of Thales Cryogenics and the recent developments with respect to this product range. For linear Stirling and pulse-tube coolers, an update will be given regarding advances in active vibration reduction.

Presently available fully adaptive Active Vibration Reduction electronics are presented and developments in the miniaturization of active vibration reduction are discussed. Results are presented of tests performed using commercial off-the-shelf drive electronics applied to linear Stirling coolers. Also, measurements with low noise force transducers rather than standard accelerometers are presented.

For Rotary Stirling coolers, recent developments will be presented which have resulted in a new design for high-efficiency digital drive electronics, suitable as a drop-in replacement for legacy analog controllers.

INTRODUCTION

Cooler Drive Electronics (CDE) is the electronic interface between the cryocooler and the system it is used in. It provides several functions:

- Provide regulated power to the cooler;
- Provide that power at the correct voltage, frequency, and sequence;
- Regulate the power to the cooler in order to maintain a stable detector temperature;
- Measure the detector temperature;
- Communicate with the system-level electronics about system status.

A block diagram of a cooler drive electronics is shown in Figure 1. The central component is the controller, typically a Digital Signal Processor (DSP) or microcontroller with relevant firmware. The connection points to the system are shown to the left. A regulated DC voltage bus provides the power to the CDE. Internal power supply electronics regulate and distribute this power to the different blocks.

Communication with the external system can take place by means of dedicated I/O lines, such as a cooler ready line, remote on/off line, standby function, or via a serial communication line such as RS232.

Analog interfacing takes place between the CDE and the temperature sensor in the detector, typically a diode or resistive sensor. A bias supply provides the necessary bias current for

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temperature sensors. The analog input circuitry provides amplification of the sensor signals and conversion to digital for use in the controller.

The controller drives the power stage, which provides the power to the cooler. The power stage uses pulse-width modulation (PWM) based output stages for high efficiency. The number of phases can differ per cooler type. CDE for linear coolers use two phases. Rotary coolers use three phases. Output power is monitored and read back by the controller for measurement purposes. In case the CDE is used for driving a rotary cooler, the Hall position sensors are read back for motion control. This is the only component in the CDE block diagram that applies specifically to rotary drive electronics. The rotary-specific components are indicated with dashed lines.

On-board memory is used for storage of data. In this memory, settings and configuration data is stored. Also, on-board memory is used for diagnostic purposes. The running hours and on-off cycles can be logged, but also more elaborate logging and analysis of measurement data can be used to perform predictive diagnostics [2].

Usage conditions and requirements for rotary and linear CDE are different. In order to maintain high system efficiency, rotary CDE has more stringent requirements for internal power consumption, due to its relative low output applications. On the other hand, linear CDE require higher output power and currents. This means that typically the power stage of rotary and linear CDE will differ in practice. For the other components, functionality and requirements are identical, hence that for Thales' CDE, similar platforms will be used for both types.

COOLER TRENDS AND DRIVE ELECTRONICS REQUIREMENTS

High Operating Temperature (HOT) detectors are a recent trend in cooled detector systems. Increasing detector temperatures (120 – 180 K) lead to both lower detector losses and higher cooler efficiencies. As a consequence, required input powers to the cooler will reduce significantly. Typical steady-state powers for High Operating Temperature detector systems are of the order of a few watts. Despite the efficiency difference between linear and rotary coolers, absolute power levels will not differ too much. This eliminates the difference in usage conditions for linear and rotary CDE.

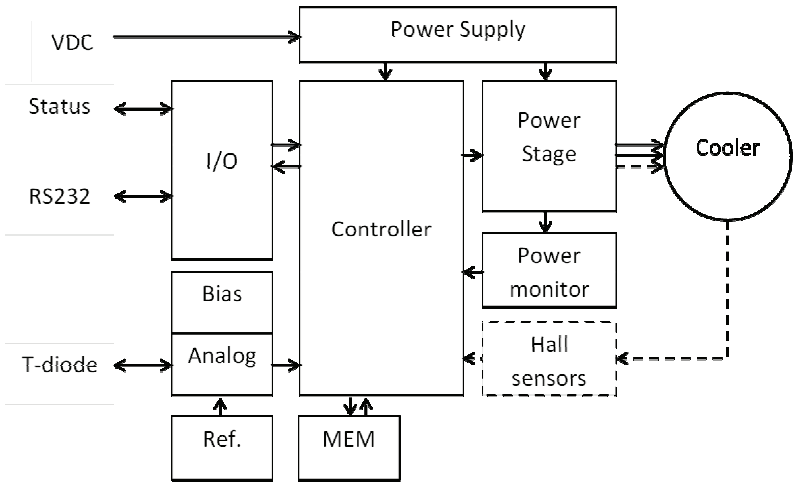

Figure 1. Block diagram of Cooler Drive Electronics. This block diagram applies to both Rotary and Linear CDE's. The only difference between linear and rotary electronics is the connection to the cooler; in rotary CDE multiple phases are needed, and often a feedback of Hall position sensors is necessary. Rotary-specific components are shown in dashed lines.

For non-military applications, such as lab equipment, scientific equipment, sensor cooling, etc., cooler drive electronics need to be flexible. In these applications, linear coolers are the most used cooler types. Different sensor types should be connectable, and the user should be able to easily reconfigure settings such as temperature set points, drive voltages, etcetera.

In order to minimize influence of cooler vibrations in these kinds of applications, cooler drive electronics preferably include Active Vibration Reduction. Active Vibration Reduction (AVR) actively reduces the cooler-induced vibrations using a feedback loop with a vibration sensor, and independent drive of both linear motors. In conventional applications this is used in combination with pulse-tube coolers. In this paper, we will also present active vibration reduction on linear Stirling coolers. The principle of AVR is shown in figure 5. In this figure, a photograph of the CDE7232 is shown. This CDE is the bench top electronics for flexible use, suitable for coolers up to 200W input power, variable frequency, diode and RTD type of temperature sensors, and configuration through a front panel interface or via an external interface bus and a PC.

DEVELOPMENTS IN ROTARY COOLER DRIVE ELECTRONICS

As mentioned before, power consumption requirements for rotary cooler drive electronics are stringent. In order to get high overall system efficiency, internal power consumption of the CDE needs to be as low as possible.

Legacy technology uses an ‘analog’ approach. Dedicated IC’s generate the required AC wave form to drive the cooler. Adjustment of set point was done by adjustments in the analog sensor circuitry. Because no controller or other logic was available, no communication other than a few status lines was possible.

Recent advances in controller and power supply components allowed the use of intelligent, ‘digital’ components. This led to the architecture comparable to linear CDE, as shown in figure 1. In table 1, a short performance comparison is made for three generations of rotary CDE is given. If two numbers are given for efficiency, the lowest number is given for the version with a so-called booster, which is needed if motor voltage is higher than the available drive voltage. The efficiency of the first-generation digital is also including a voltage booster.

In Figure 2, a photograph of two versions of the new-generation digital cooler drive electronics is shown. On the left, the version of which the footprint is compatible with the legacy analog electronics. On the right the version with round footprint (still placed within its rectangular carrier). The dimensions of the rectangular carrier are also identical to the legacy analog footprint.

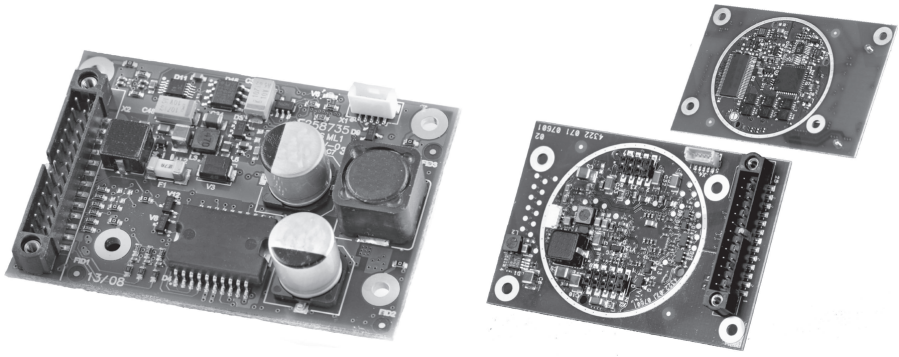

Figure 2. Photographs of new generation Rotary Cooler Drive electronics. Left is the footprint compatible with legacy analog controllers. Right is the round footprint for mounting inside the housing of the rotary cooler.

Table 1. Overview of different generations rotary cooler drive electronics.

	Legacy analog	First gen. digital	New gen. digital
Efficiency	>65%	80%	>85%/>90%
Temperature stability Short term	0.04 mV	0.04 mV	0.02 mV
Temperature drift Long term	4 mV	0.4 mV	0.4 mV
Power supply voltage	9-18Vdc or 18-36Vdc	7.5 – 12Vdc	7.5 -28Vdc
Board dimensions	63x43mm	63x43mm	40mm round

The performance difference between analog and digital versions can be mainly seen in the long term stability (drift). The step between first and current generation digital cooler drive electronics is especially visible in further efficiency upgrades, miniaturization, and flexibility. Functionality can be added by modifying firmware. Diagnostic functionality, elapsed time counter or predictive diagnostics can easily be implemented.

Footprints of the analog and first generation digital are identical. Current generation digital is also available in the same footprint as the legacy versions for compatibility reasons. However, the same electronics is available in a round footprint, for integration within the housing of the cooler itself.

The short-term temperature stability of three versions of rotary drive electronics has been measured. The short term temperature stability of the analog electronics is shown in Figure 3. A comparison of first generation and new generation CDE are plotted in Figure 4. Both graphs show results at different set points. It can be seen that both of the new digital versions show stability within the 10uV range. Temperature stability of the analog and first generation digital are comparable, and both within the 50uV range.

All curves are measured using the same cooler (RM4). It should be noted that these stability figures are determined at stable conditions, such as drive voltage and ambient temperature.

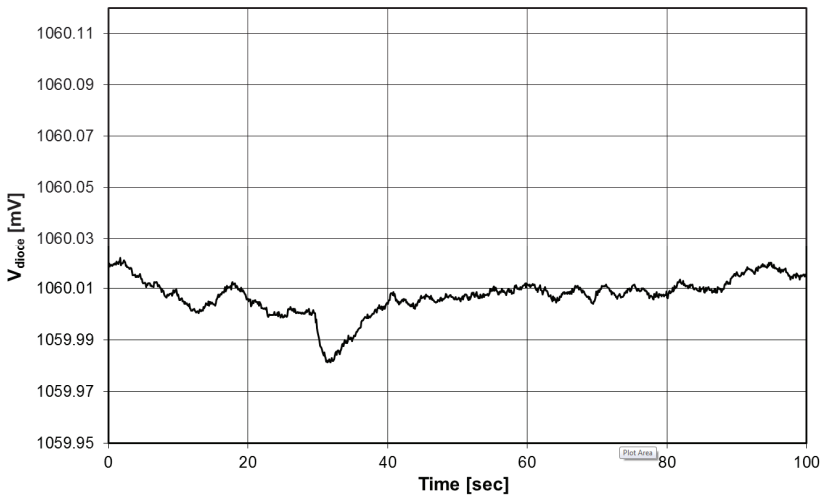

Figure 3. Short term temperature stability of analog rotary Cooler drive electronics.

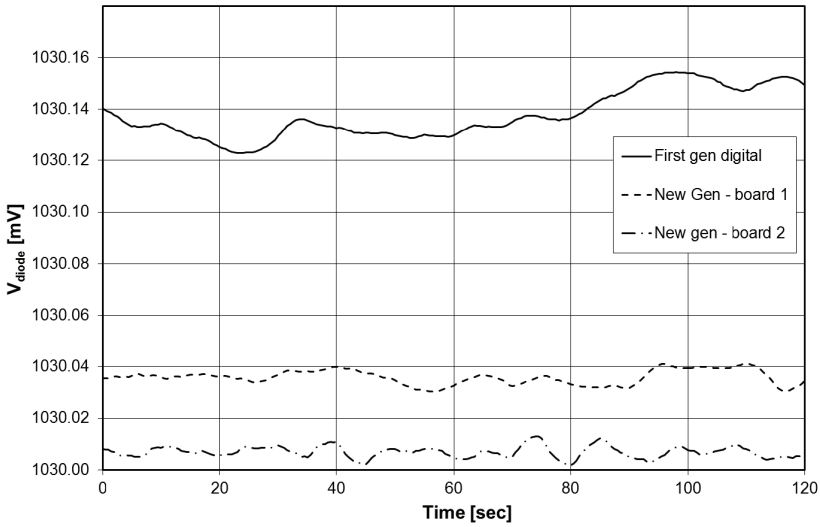

Figure 4. Short-term temperature stability of two generations of digital rotary CDE.

The current generation digital RDE is designed to be placed within the motor housing of a rotary cooler, hence the round footprint. In the photograph of Figure 2, the round footprint is placed on a square PCB of equal dimensions as analog and first-generation digital electronics.

As mentioned in the introduction, for low-power, HOT applications, differences between rotary and linear CDE are negligible. HOT versions of both linear and rotary CDE are thus foreseen to fit within the 40 mm diameter envelope.

DEVELOPMENTS IN LINEAR COOLER DRIVE ELECTRONICS

Active Vibration Reduction

Exported vibrations have always been an important point of attention for mechanical cryocooler systems. In vibration-sensitive applications, typically pulse-tube coolers are used for minimum vibration generation [2]. Pulse-tube coolers have only moving parts in the compressor. When the compressor is of the dual-opposed piston type, theoretically there is no vibration export. Any induced vibration in such case is due to small imbalances due to tolerances in parts, materials, and processed. The residual vibration can be further reduced passively (e.g. with suitable suspension for the compressor), or actively, using so-called active vibration reduction.

The classical approach to AVR is shown in Figure 5. Cooler drive electronics with AVR drive both linear motors in a cooler separately. A vibration sensor such as an accelerometer is used to measure the induced vibrations. An adaptive feedback loop [2] drives both motor halves independently to reduce the induced vibration. Another, independent, feedback loop is used to maintain stable cold tip temperature.

In Figure 5, the CDE7232 cooler drive electronics is shown. This is a bench top cooler drive electronics, suitable for a wide range of linear cooler types. This CDE has AVR functionality.

Active Vibration Reduction on Linear Stirling Coolers

Recently [3], TCBV has demonstrated that the same AVR principle can also be used to reduce the vibrations in a Stirling cooler. A Stirling cooler is by definition unbalanced because of the moving mass of the displacer. For Stirling coolers, AVR is then used to balance the system's all three moving masses.

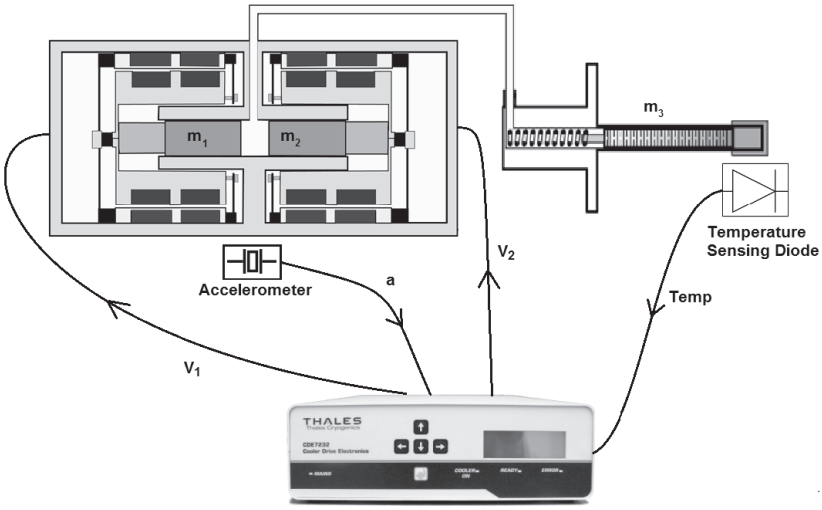

Figure 5. Schematic overview of Active vibration reduction. The Cooler drive electronics drives the two compressor halves independently (V1, V2). Correction signals are determined in a feedback loop, with sensor input from a vibration sensor such as an accelerometer. An independent temperature control loop maintains a constant detector temperature.

In [3], it is shown that the balancing of displacer vibrations can be done with the motion of the compressor pistons. AVR on Stirling coolers has a small influence on efficiency. The additional motor force does not entirely contribute to the cooling mechanism. It is shown that the impact on efficiency is mainly determined by the cold finger induced vibration force, the compressor motor force characteristic, and the dynamic impedance of the linear motor. Quantitatively, the impact on efficiency is small. It is of the order of one percent. AVR on a Stirling cooler requires that both the compressor and cold finger are mounted rigidly on a single frame. They need to be coupled mechanically for all the forces to balance out.

Examples of Mounting Frames

In Figures 6 and 7, the induced vibrations for two Stirling coolers are plotted, with and without AVR. Vibrations are measured with a B&K accelerometer placed on the mechanical interface flange of the cold finger. Only vibrations in the principle axis of motion of the displacer are plotted. Figure 6 represents the induced vibration force on an LSF9350, 8W class Stirling cooler. Figure 7 represents the LSF9997, a 1 W class Stirling cooler.

The effective reduction rate is a factor 50 to 100. This brings the induced vibration level of both Stirling coolers to similar levels as pulse-tube coolers, while maintaining the high efficiency of Stirling coolers.

For both the large and the small scale cooler, the absolute vibration level with reduction is of comparable level. This is caused by the resolution of the used accelerometer. In the example of Figures 6 and 7, low-cost accelerometers are used. These are limited in signal to noise ratio. Another drawback of using accelerometers is that there should be a degree of freedom in motion of the system. This means that the system needs to be suspended flexibly, which could lead to further challenges in terms of system integration. Heat sinking becomes more difficult, and robustness against environmental shock and vibrations might be worse.

These difficulties can be overcome by using force transducers instead of accelerometers. An experiment was done with Kistler force transducers. Device under test was an LPTC compressor. The signal of the force transducers was fed into the CDE7232. The results with and without AVR are shown in Figure 8. Again, a reduction of about 50 times was achieved. So it can be concluded that AVR can be successfully applied using different vibration sensor types.

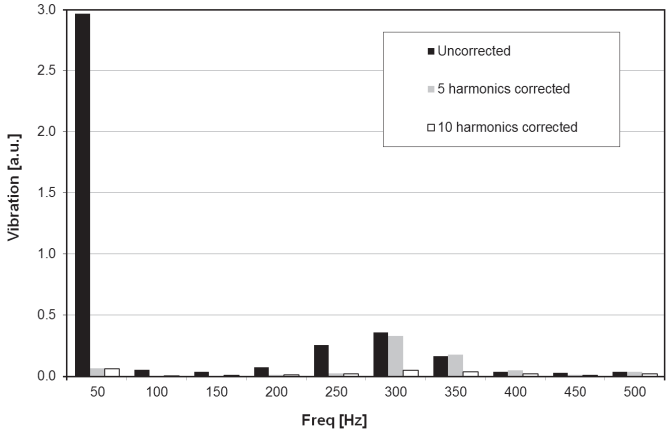

Figure 6. Induced vibrations of the LSF9350 cooler, measured on the cold finger flange, with and without AVR. The amount of suppressed harmonics can be adjusted, results for 5 and 10 suppressed harmonics are plotted.

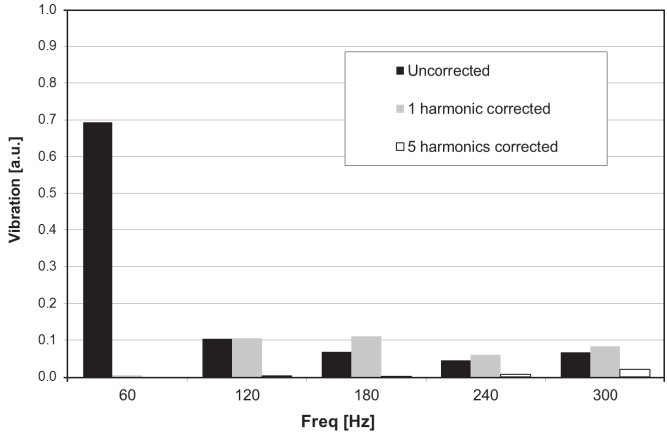

Figure 7. Induced vibrations on the LSF9987 cooler, with and without AVR. Measured on the cold finger flange. No suppression was visible beyond the fifth harmonic.

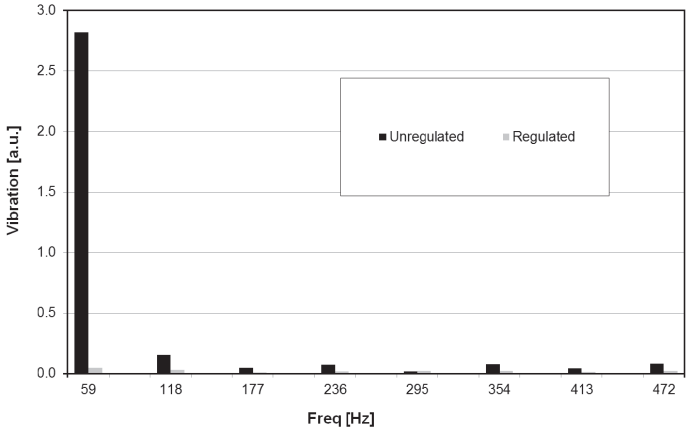

Figure 8. AVR measurements on an LPTC compressor, using the Kistler force transducers in the AVR feedback loop.

CONCLUSIONS

Recent developments in both linear and rotary cooler drive electronics have been reported. It has been shown that by using modern, high-efficiency digital components in rotary CDE have led to electronics that are smaller, more stable, more flexible, and more efficient. It was also shown that CDE for HOT detector systems will be significantly smaller than existing boards.

It was shown that Active Vibration Reduction can be used not only on pulse-tube coolers, but also on linear Stirling coolers. With AVR, the residual vibrations due to displacer motion can be suppressed to levels comparable to similar sized pulse-tube coolers. This can be done using off-the-shelf electronics and coolers.

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