Development and modification of National Instruments Data Acquisition hardware for use in the centrifuge environment

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ABSTRACT: This paper details the modification of a commercial data acquisition system for use in a geotechnical centrifuge. As with many 'off-the-shelf' components put into service within the harsh high stress centrifuge environment, they are not originally conceived to operate under these extreme conditions and thus it is not uncommon for high failure rates to occur in standard hardware items. In many cases successful modification can be implemented to strengthen standard components to enhance their robustness and operation. In this respect, this paper reports on difficulties experienced in the operation of a National Instruments PXI chassis system and its failure in the high gravity environment. Specific problems identified relate to fragility of the cooling fan systems that generate fault conditions that trigger auto shut down sequence of the chassis. A bespoke solution is developed and documented that has been successfully implemented to circumnavigate and mitigate fan failures.

1 INTRODUCTION

1.1 *50gT Centrifuge and data acquisition system*

The University of Sheffield established a geotechnical centrifuge research facility in 2013 which is located within the 'Centre for Energy and Infrastructure Ground Research - CEIGR' (Black 2014). The main research centrifuge is a 4m diameter 50gT research machine that is capable of accelerations up to 150 times earth's gravitational acceleration (g) (Fig.1). A National Instruments (NI) data acquisition PXI system serves as the primary data capture system.

Figure 1. UoS-50gT 4m diameter centrifuge.

A PXIe-1085 18 slot data chassis is mounted within the centrifuge storage cabinet which enables a range of data capture cards to be integrated with the hardware controller. PXI systems are commonplace in industrial and laboratory environments and are capable of performing a wide range of functions at high speeds including general data acquisition, actuator/motor control, fibre-optic sensor measurement and image acquisition and analysis. National Instruments LabVIEW software allows for rapid development of experimental data acquisition and control systems with seamless integration to PXI hardware; saving a significant amount of low-level development and systems integration effort. The ability to incorporate a wide variety of instrumentation and control of a large range of experimental test apparatus make the PXI platform and LabVIEW software ideal for use in centrifuge test developments where a large number of different sensors and actuation systems are typically utilized.

1.2 *PXIe-1085 chassis and cooling system*

The PXI chassis system is a modular design allowing a variety of different hardware to be integrated within it via the unit's expansion slots. An embedded PC module performs the synchronization and control of the integrated modules. The CEIGR PXIe-1085 chassis has 18 slots where 2 slots are used for the embedded controller PC (PXIe-8135) a further 4 slots are used as the centrifuge primary data acquisition system (DAS); allowing interfacing of up to 150 sensors simultaneously as well as providing analogue outputs and digital Inputs/Outputs. Image acquisition, motion control and a fibre-optic sensor interface modules are also provided (Fig. 2).

The universal nature of the chassis and the large range of modules available require that considerable power is provided by the modular power supply embedded in the chassis. This in turn necessitates a cooling system capable of keeping the chassis temperature within acceptable operational limits to safeguard the performance of the hardware. As the current draw from the modules is high, a significant amount of heat energy can be generated when all cards are plugged in.

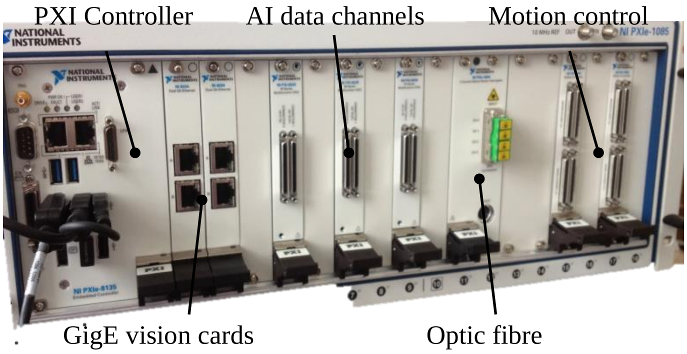


Figure 2. UoS50gT NI PXI DAS.

The primary NI cooling solution for the PXIe-1085 chassis is via 3 external high-speed and high air-flow fans, rated at 4800 RPM and 169 CFM, the cooling capacity of the fans sufficiently ventilates the chassis. The fan dimensions measured 120 mm^2 by 40 mm depth and were mounted in support housings at the rear of the chassis as shown in Figure 3.

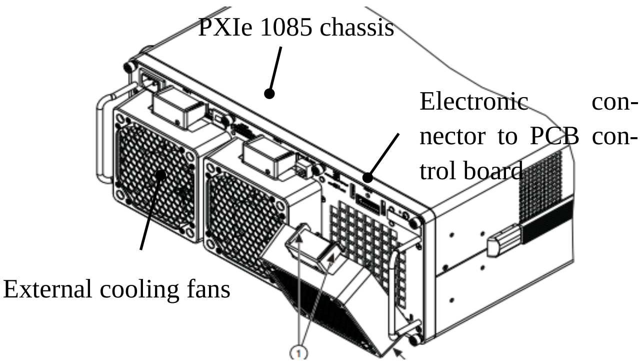


Figure 3. External fan connection to PXI chassis (after National Instruments, 2013).

The speed of the fans, as determined from their tachometer output signals, along with internal temperature measurements, derived from 5 thermocouples, is continuously monitored by a sophisticated integral chassis controller that operates an internal health monitoring program. If the temperature recorded by any of the thermocouples exceeds 70ºC, the chassis controller will initiate a safe shutdown of the system. Similarly, if the speed of two or more fans drops below a pre-determined input range, for example fan speed falling below ≈4000 RPM, shutdown is also initiated. The chassis controller operates with some fan redundancy such that the system will continue to operate normally if failure of a single fan occurs. Auto safe-shutdown is initiated if two or more fan failures occur simultaneously. Clearly, any fragility in the data acquisition and centrifuge systems are unacceptable and thus should be prevented.

The primary external cooling fans have two modes of operation, auto and default. In auto mode the fan speed is modulated to maintain the temperature whilst keeping the acoustic emissions to a minimum (at maximum speed the fans generally provide excessive cooling for most PXI system configurations). The modulation is achieved through Pulse Width Modulation (PWM) of the supply voltage such that fan current consumption and hence speed and air flow can be controlled. In default mode, the supply voltage is kept constant at 12V DC and the fans operate at their maximum speed and capacity. For the work reported herein, note that the default option mode was selected so as not to complicate the revised control process of the software modifications implemented.

Additional to the external rear mounted fans, the internal high capacity power supply operates two smaller dedicated cooling fans that are embedded within the modular Power Supply Unit (PSU). These fans measure 60 mm^2 by 20 mm depth, and are also monitored by the chassis health monitoring controller. Failure of these fans also triggers a chassis shutdown event although no difficulties have been witnessed with these fans owing to their orientation with respect to the acceleration gravity field, small self-weight of the rotating fan and robust internal bearing; thus modification of these fans and their control electronics is not within the scope of this paper.

2 TECHNICAL CHALLENGES

2.1 *Chassis structural integrity*

As with many 'off-the-shelf' components put into service within the harsh high-stress centrifuge environment, they are not originally conceived to operate under these extreme conditions and thus it is not uncommon for high failure rates to occur in standard hardware items. This paper reports on difficulties experienced in the operation of a National Instruments PXI chassis system and its failure in the high gravity environment. Specific problems relate to the fragility of the cooling fan system that generates fault conditions during operation that trigger auto shut down sequence of the chassis.

The PXI system was installed into the central cabinets of the centrifuge via a standard 'off the shelf' NI rack mounting kit bolstered by additional custom support bracing along the sides and back of the chassis that interfaced with the main structural members of the data cabinet (Fig. 4). This was necessary to ensure that the self-weight of the chassis unit and internal cards, approximately 18 kg, would be secure once subjected to increased body forces imposed by the centrifugal force during operation.

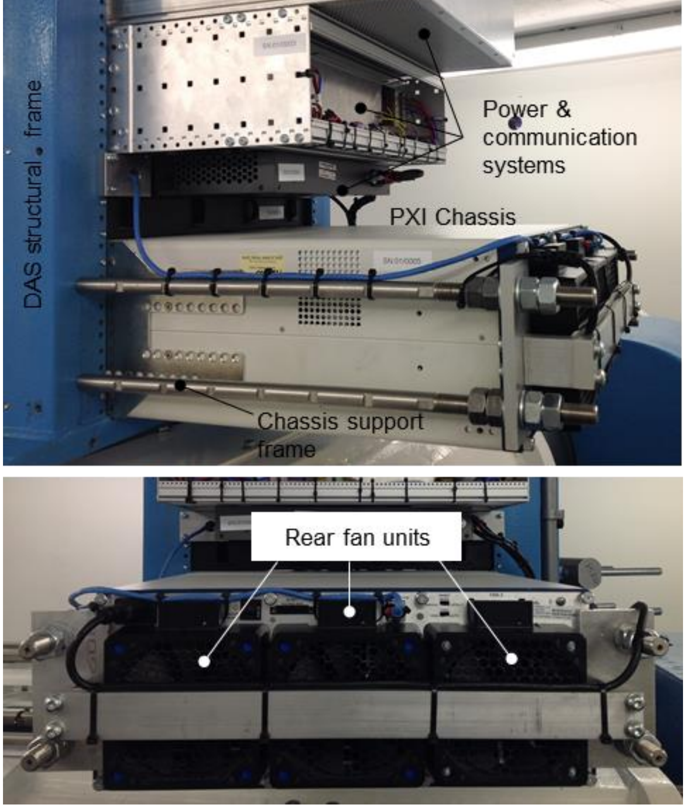


Figure 5. PXI chassis and fan systems.

2.2 *Fan operation*

The orientation of the chassis in the data cabinet places increased stress on the fan units as they rotate in under elevated gravity. The back of the chassis is located at a distance of 0.7 m away from the centre of rotation, meaning that at the highest machine speed of 281 RPM (150g at an effective radius of 1.7 m) the fan could experience up to 60g.

The fan blade is mounted using a magnetic bearing which is sensitive to vibration/increased forces produced during rotation that has the potential to unseat the blade assembly leading to mechanical failure. Furthermore, the increased body weight forces associated with the fan blade while operating under stress requires greater electrical power and current draw to maintain rotation speed. If the gravity forces are excessive it can lead to (i) a fan stall condition, (ii) laboured rotation (reduced RPM), and (iii) high wear of the bearing component that leads to premature failure or unreliable performance.

Clearly any potential risk of such failures in detrimental to the continued and repeatable operation of the centrifuge facility and failure/maintenance downtime should be minimised. The aspect of system fragility was investigated as part of the commissioning sequence whereby it was necessary to implement bespoke modifications to increase the resilience of these systems, which is described below.

3 METHODOLOGY

3.1 *Auto-shutdown of the PXI system at g*

A LabVIEW virtual instrument (VI) was developed to monitor chassis health parameters such as temperature, fan speed and supply voltage levels during centrifuge testing of the PXI system. The VI was run on the embedded controller located in the PXI system and monitored via a remote connection from a PC located in the CEIGR control room. To commission the system, the centrifuge speed was increased to generate ascending levels of acceleration (as experienced at the swinging platform of the machine) in steps of 10g, with the intention of reaching a maximum acceleration (g-level) of 150g. At around 90g, the PXI system went into auto shutdown and the remote connection to the embedded controller was lost.

Subsequent post-test investigations revealed that the shutdown had been initiated due to sudden fan failure. No indication of either reduction in fan speed or increase in chassis temperature was observed prior to the shutdown. After performing some independent tests on one of the fan units it was determined that the fan rotor could be moved both vertically and horizontally on the magnetic bearing with relative ease and therefore significant deflection of the rotor was most likely to occur during high gravity situations where its self-weight is increased. Inspection of the fan casing showed that scour marks were present and it was therefore concluded that the fan rotor had indeed come into contact with the casing, causing a sudden loss of speed on at least two of the three units, and shutdown of the system.

3.2 *Modification of PXIe chassis cooling system*

It is well understood that as a centrifuge rotates the airflow through the chamber is significantly increased with the rotational speed on the machine. This effect is apparent during testing where strong air currents are observed to circulate from the chamber into the laboratory environment. This in-effect provides considerable cooling potential, particularly towards the central axis of the machine where air can pass freely into the chamber through the perforated roof cover. It was decided that this airflow could be utilized for the purpose of providing secondary vented cooling to the PXI chassis during tests and preliminary calculations determined that sufficient airflow could be achieved. Provision of this artificial cooling would then allow for the chassis fans to be switched out during centrifuge operation to prevent damage to the fans and system failure.

In order to run the chassis without fans, and prevent it from entering auto-shutdown, a means had to be found to simulate the tachometer-generated feedback signal which the chassis controller monitors to determine fan faults. Following discussion with NI technical representatives a potential work around solution was conceived.

3.2.1 *Proposed technical solution*

Figure 6 shows the specified output waveform from the tachometer where two pulses are provided per fan revolution.

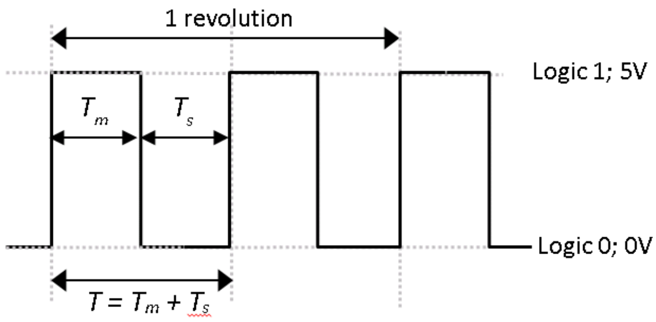


Figure 6. Fan tachometer signal

The fan is powered by a 12V DC signal, generating the maximum rated speed of 4800 RPM. The tachometer output of the fan was measured using an oscilloscope to determine the frequency, *f*, and the mark space ratio, T_m/T_s, where T_m is the mark period, or on time, and T_s is the space period – the off time. The fan has an open collector output which means the logic 1, 5V DC signal is generated by the sink of the digital input – the signal is pulled high internally by the data acquisition via a resistance. To achieve this, the signal was connected to a digital input of a National Instruments 6000 USB device and the input was directly measured with the oscilloscope. The signal has a mark to space ratio of 0.5, therefore, the on-period, T_m, and off period of the signal are equal, and were measured to be ≈3.1 ms. The waveform frequency was approximately 161 Hz, corresponding to a rotational speed of ≈80 RPS or 4850 RPM.

The next logical step was to feed a generated square wave signal of ≈160 Hz into the tachometer input of the chassis. This signal is required in order to satisfy the chassis controller and health monitoring system to switch on the system and thus would mimic that a fan was connected and running at the demanded speed. To accomplish this, a function generator was set up to output a 160 Hz square wave (alternating between 0 and 5V DC). The chassis controller will initiate auto-shutdown after it has determined that two of the three fans are not responding at the demanded speed. In order to test this solution, two fans were removed and the square wave was fed into the chassis tachometer input of one fan. If the square wave signal was rejected by the chassis controller, then it would lead to an auto-shutdown as it would determine only a single fan was present. It was found that the simulated signal was able to satisfy the chassis fan monitor, and the PXI system started up successfully and remained operational. When the frequency of the generated signal was dropped below 135 Hz (corresponding to a rotational speed of 4050 RPM) the chassis went into auto-shutdown mode.

Hence, relying on system cooling via the natural airflow within the chamber, and simulating an input fan signal while the centrifuge was rotating would allow for the fans to be switched off inflight thus protecting the bearing systems and preventing initiation of auto shutdown.

3.2.2 *Technical solution hardware*

Figure 7 gives an overview of the modified PXI system, showing the various elements required to control the fans and supply the simulated signal. External fans that are affected by this solution are indicated by numbers 1 to 3; internal fans associated with the PSU that are not modified are labelled 4 and 5.

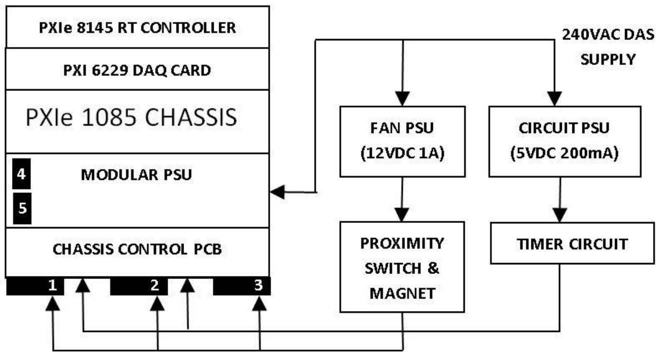


Figure 7. Modified chassis overview.

3.2.3 *Timer circuit*

A commonly used method for generating a square wave is the 555 timer circuit, as shown in Figure 8. The circuit was built to simulate the tachometer waveform required to satisfy the chassis health monitoring system. The 555 timer circuit operates in an astable mode of operation to produce a square wave with mark to space ratio of 0.5 (50% duty cycle).

The time period, *T*, for a complete square wave cycle is determined from frequency, *f*, by values of *R* and *C* and is given by Equations 1 and 2.

$$f = 1.44/2RC \quad (1)$$

$$T_m = T_s = 0.69RC \quad (2)$$

The on-time, T_m, and off-time, T_s, are half the time period, *T*, since the square-wave has a 50% duty-cycle. The value of the charging capacitor (*C*) was chosen to be 10 nF. Therefore, from rearrangement of Equation 2, to generate a wave form with an equal on/off time of ≈3.1 ms the value of *R* should be 447KΩ. The actual value of resistance used was 470KΩ, resulting in a waveform with a frequency of

153 Hz equating to a simulated fan rotational speed of 4590 RPM and an on/off pulse time of 3.2 ms.

A transistor was connected to the output of the circuit to match the tachometer open collector output. The output of the open collector was connected to the fan tachometer inputs circuit using coaxial cable to minimize induced signal noise.

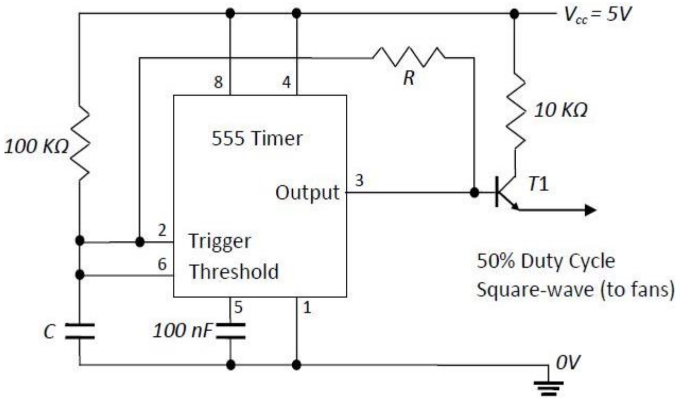


Figure 8. 555 timer circuit in astable output mode.

3.2.4 *Control of fan power*

The fans must be active at 1g in order to adequately cool the system in the absence of centrifuge generated airflow. This is achieved by feeding a 12V DC PSU fan power supply through a magnetic proximity switch. The switch connection is made when the switch comes into close contact with a magnet. The switch and magnet were mounted such that the power connection is made only as the machine's swing platform is parallel to the ground (i.e. when the machine is at rest at 1g). Mounting and operation of the sensor and magnet is shown in Figure 9.

3.2.5 *Replacement of NI modular fan units*

It was decided to replace the NI modular fans (manufactured by JMC Products), shipped with the PXIe-1085 chassis with commercially available fans. This was mainly owing to (i) due to depth of the fan unit, the NI fans left very limited space inside the casing for connection of the external power and tachometer signals, therefore it was decided to opt for a lower profile fan, and (ii) several readily available fans offered lighter weight fan rotor blades and more robust bearings.

The replacement fans have significantly lower airflow, static pressure and speed; however this is not problematic as the full cooling capacity of the NI fans was determined excessive for foreseeable chassis configurations, with some margin of surplus cooling. Temperature monitoring of the chassis at 1g indicated no additional change in chassis temperature. Furthermore, the issue of fan robustness and ability to operate continually at high gravities was no longer a concern given that the technical solution implemented switches them off during tests. This is advantageous in prolonging the serviceable life. Despite this successful solution, note that fans are changed out at regular intervals during routine maintenance and servicing to minimize any possible bearing fatigue issues.

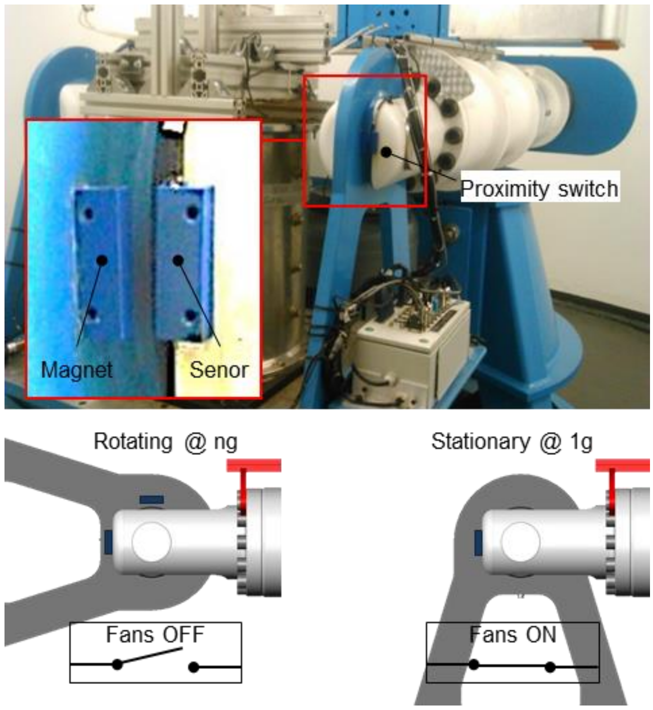


Figure 9. Proximity switch senor

3.2.6 *Modification of cabinet shroud*

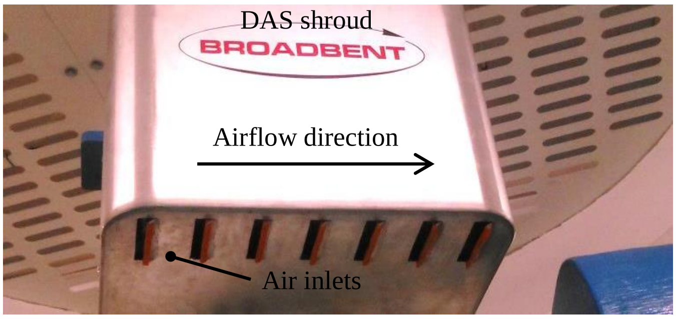
As the cooling solution focused on utilizing the natural airflow during rotation of the centrifuge, it was necessary to increase the airflow into and through the NI chassis. A shroud covers the back of the data cabinets to restrict access, protect the electronic systems and reduce the wind pressure during rotation. To generate the necessary airflow into and through the shroud design, inlet perforations were formed in the underside of the shroud as shown in Figure 6.

In order to force air into the cabinet during centrifuge rotation, the inclusions incorporated a flanged section angled towards the direction of rotation. Internal ducting directs the airflow through the now stationary fans at the back of the chassis unit. The worked air that is now warm exits the chassis and shroud via venting slots on the top of the cabinet which provides natural convective airflow.

4 RESULTS

Once the modification to the chassis cooling system had been completed a number of tests were conducted to monitor the temperature profiles within the chassis in both static and high gravity conditions, with fans switched on (at 1g) and off (during spinning). A simple resistance based sensor was developed to monitor the total current being drawn by the replaced fans to determine both fan failures and their operational state.

Figure 10. Modified shroud with air inlets.



Test g-level was measured using a MEMS accelerometer mounted on the platform. Figure 11 shows the fan current and g-level (experienced at the platform) at the start and end of a typical test.

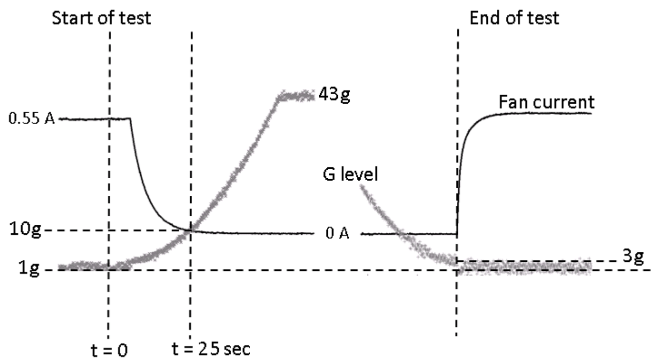


Figure 11. Fan switch on/off characteristics with g-level.

Figure 11 also illustrates that total fan current reaches 0A (indicating fans are off and stationary) at around 25 seconds after the machine has started to rotate. At this point the machine has reached an acceleration of around 10g and the swing platform has rotated sufficiently to activate the magnetic proximity switch. The fans are re-activated again when the machine drops below an acceleration of 3g. The total current drawn by the fans is 0.55A, which corresponds with the rated current of 0.18A per fan. The characteristic shows that the desired automatic control of fan state was achieved.

Figure 12 shows the average internal temperature of the PXI chassis prior to and during a typical test. The test involved spinning the machine at accelerations of 25, 50, 75 and 100g. Prior to the test, the chassis was left running for a period of around 210 minutes to assess the cooling performance at 1g. For the first 100 minutes the cabinet door was opened to allow the air to circulate. After 100 minutes the cabinet door was closed, leading to a transient heating effect as shown in the plot where the average temperature climbed to around 31ºC. Subsequent tests of the system at 1g over several hours has shown that the temperature eventually reaches a steady state of around 35ºC with the cabinet closed. This is significantly below the chassis' upper ambient operational temperature limit of 70 ºC stated in National Instruments (2015).

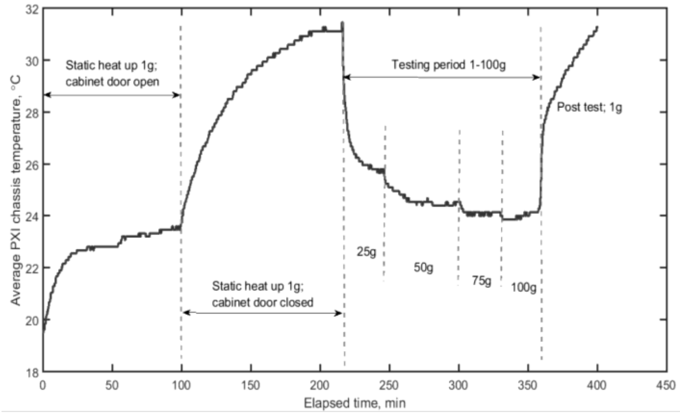


Figure 12. Cooling performance prior-to and during testing.

Figure 12 shows an immediate cooling effect when the machine is running (after around 215 minutes). At an acceleration of 25g the average temperature drops to ≈26ºC. Further increases in acceleration caused the temperature to drop further until it reached the ambient temperature of the chamber (≈24ºC). After around 360 minutes the machine was stopped and the fans activated. The figure confirms that the strategy of relying on natural ventilation and switching out of the cooling fans is highly effective in providing the required system cooling and preventing gravity-induced damage to fans during centrifuge operation.

5 CONCLUSIONS AND FURTHER WORK

The paper describes an improved modifications to a National Instruments PXIe-1085 chassis cooling system which was successfully adapted in order to operate in the harsh high-gravity environment of a geotechnical centrifuge. Fan tachometer signals were emulated using a 555 timer circuit to generate a pulsed waveform. The waveform was fed into the chassis controller circuitry and enabled the PXIe chassis to successfully operate in the high gravity field during centrifuge operation.

6 REFERENCES

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