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Diesel-Driven Compressor Torque Pulse Measurement in a Transport Refrigeration Unit

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ABSTRACT

When an open drive compressor is directly coupled to a Diesel engine in a Transport Refrigeration Unit (TRU), the torque pulses between the compressor and engine can have significant effects on the TRU control strategy and compressor reliability. Understanding the torque interaction between the compressor and engine during transient conditions is also critical to ensure the power limitations of the engine are not exceeded. Although torque data is typically available from engine manufacturers, it is not fully representative of the torque signature seen in the engine’s final application. Due to emission regulations and higher efficiency requirements, advances in Diesel engine technology have resulted in higher torque pulses. For these reasons, it is necessary to measure the torque interaction between the compressor and engine in the TRU.

To study the interaction between the compressor and engine, two torque measurement devices were applied to a TRU. The torque signature was studied during compressor part load operation, transient events, multiple speeds, and start/stop. The torque measurements were then made available as inputs for stress/strain analysis, torsional analysis, harmonic analysis, reliability predictions, and TRU controls development. This paper discusses the tradeoffs of the different measurement devices, the experimental test configuration, the experimental method and the test results.
1. INTRODUCTION

In a Transport Refrigeration Unit (TRU), a diesel engine is commonly used as the prime mover, which directly drives an open shaft refrigeration compressor. In the TRU application, unloading compressors can be utilized to improve system efficiency and control the load on the diesel engine. Controlling the load on the diesel engine can have a direct influence on engine emissions and regulatory compliance. One of the TRU’s primary objectives is to lower the temperature in the cargo area as quickly as possible, until the desired temperature has been achieved. While lowering the temperature in the cargo area, the compressor can often times demand more power from the diesel engine than what it can provide. To accommodate this situation and prevent the engine from stalling, compressor unloading can be utilized to reduce the load on the engine. For this reason, it is necessary to understand the interaction between the compressor and engine during compressor unloading.

Typically, compressor performance testing is conducted on a calorimeter facility, which uses an electric motor to drive the open shaft compressor. This type of testing is beneficial for understanding compressor performance, but it is ineffective for understanding transient operating conditions. In addition, calorimeter testing doesn’t provide information about the interaction between a diesel engine and an unloading compressor. To understand the interaction between a diesel engine and an unloading compressor, a different Experimental Test Setup and Method must be used.

2. EXPERIMENTAL TEST SETUP

A Thermo King TRU is shown in Figure 1. Located at the bottom of the unit, the power package consists of a compressor (left side) directly coupled to a 4-cylinder, 4-stroke diesel engine (right side). An internal plastic bulkhead (not visible) isolates the environment of the engine compartment from the refrigerated cargo area inside the trailer. Behind the bulkhead, a fan and evaporator coil provide conditioned air to the payload inside a trailer. The engine operates at one of two fixed speeds depending upon the cooling requirements of the cargo.

A torque-sensing instrument was installed between the engine flywheel and the input shaft of the compressor. The engine flywheel housing was extended by using a custom-machined extension ring made from aluminum. This extension ring separated the compressor from the engine and provided adequate space for installation of the torque sensor (See Figure 2).

Seven channels of time-history data were acquired: torque, shaft rotational speed, capacity control solenoid voltage, suction temperature, discharge temperature, suction pressure and discharge pressure. A digital data acquisition instrument synchronously recorded all channels. Several digital sampling frequencies were selected: 8192 Hertz (Hz) - compressor torque demand, 1024 Hz - suction and discharge pressures, 102.4 Hz - shaft rotational speed, and 1.6 Hz -
suction and discharge temperatures. Simultaneous acquisition was performed in order to synchronize thermodynamic conditions with torque magnitudes, compressor load-unload states, and engine speeds.

A Hall Effect sensor circuit provided a sequence of voltage pulses, which the data acquisition system interpreted as a speed signal. The pressure transducers were powered using the internal power sources of the data acquisition system, simplifying calibration before each experimental sequence.

Review of measured thermodynamic data confirmed that the refrigerant’s pressure and temperature conditions reached steady-state. All seven parameters were measured at both low and high engine speeds.

3. EXPERIMENTAL METHOD AND RESULTS

To measure torque waveforms, a telemetry instrument was selected. One advantage of a telemetry instrument was that it could wirelessly transmit measurement signals to the data acquisition system. A second advantage was that the instrument did not require an external power connection to operate the internal electronics of the sensing element. A circular receiver antenna, connected to an external radio-amplifier, communicated wirelessly to the sensor electronics inside the rotating sensing element. Figure 2 depicts a three dimensional model of the telemetry instrument and the surrounding components.

![Figure 2 - Telemetry Antenna-Amplifier Instrument](image)

The output torque signal was often contaminated by over-range clipping and signal noise. Signal noise may have originated from misalignment of the outer antenna ring relative to the inner rotating sensor. The misalignment was introduced by vibration of the compressor and surrounding structures during TRU operation. The different material properties of the aluminum and cast iron mounting structures may have influenced the conductivity of the radio-frequency signals transmitted by the telemetry instrument.

A mechanical slip ring device was also used. It demonstrated the benefit of a high-level and low-noise signal, transmitted through wired connections and gold-plated contacts. However, external power was required to operate the internal electronics of the instrument. Figure 3 depicts a three dimensional model of the instrument’s components.
The torque variations of 10% load, 50% load, 90% load, and full load at low speed and high speed, with 30 second cycle duration are shown in Figures 4 and 5. The detailed wave form of low speed and high speed torque variation with 50% load are depicted for two revolutions in Figures 6 and 7. The engine speed variations of 10% load, 50% load, 90% load, and full load at low speed and high speed, with 30 second cycle duration are shown in Figures 8 and 9. The compressor discharge pressure variations of 10% load, 50% load, 90% load, and full load at low speed and high speed, with 30 second cycle duration are shown in Figures 10 and 11.
Figure 5 – Torque Measurement, High Speed

Figure 6 – Torque Measurement During 50% Load Cycle, Low Speed

Figure 7 – Torque Measurement During 50% Load Cycle, High Speed
From the torque measurement waveforms above, it can be assumed that the peaks correspond to the firing of the diesel engine. However, it is unclear which components in the system correspond to other peaks and valleys seen in the waveform. Additional frequency and system analysis may be required to decompose the torque signature and understand which components contribute to its shape.

![Figure 8](image1.png) Engine RPM Fluctuation Based On Compressor Load, Low Speed

![Figure 9](image2.png) Engine RPM Fluctuation Based On Compressor Load, High Speed
Engine speed (RPM) fluctuates based on the compressor load. When the compressor is in its unloaded state, engine speed increases in all cases. This may result in higher fuel consumption and can affect the stability of TRU components that are driven by the engine, such as generators and fans.

As expected, refrigerant discharge pressure increases as compressor load increases. When the compressor transitions from an unloaded to a loaded state, there is a rapid increase in discharge pressure. Similarly, there is a rapid reduction in discharge pressure when the compressor transitions from a loaded to an unloaded state. These peaks can be seen in Figures 10 and 11.
Figure 12 – Maximum and Peak-to-Peak Torque Variation at Each Load Condition

The maximum torque drops at 10% load and continues to increase as the percentage of load is increased. The peak to peak torque fluctuations are higher at partial loads than at full load.

Figure 13 – Maximum and Peak-to-Peak Speed Variation at Each Load Condition

The maximum speed is flat when speed changes from partial load to full load. However, the peak to peak speed fluctuations increase when partial loads are applied.
Figure 14 – Maximum and Peak-to-Peak Discharge Pressure Variation at Each Load Condition

The maximum discharge pressure drops at 10% load and continues to increase as the percentage of load is increased. The peak to peak torque fluctuations are higher at 10% and 50% load, than at 90% and full load. The discharge pressure behavior responds directly to changes in torque.

5. DISCUSSION

The torque signature depicted in Figures 6 and 7 provides a detailed view of the interaction between the engine and compressor. However, it is unclear which component is contributing to the different characteristics of the waveform. To decompose the waveform into its individual components, a Fast Fourier Transform (FFT) can be used to convert the torque signal to a frequency spectrum. With additional frequency data, it may be possible to understand how the refrigerant compression process and engine firing contribute to the torque waveform that was measured.

To better understand the torque waveform shown in Figures 6 and 7, it may also be advantageous to obtain the engine torque waveform using a constant brake load. This may help identify which peaks and valleys in the torque waveform are due to the firing frequency of the engine. Obtaining a torque signature for the compressor using an electric motor may also indicate how the refrigerant compression process affects the measured torque waveform.

As shown in Figures 8 and 9, the engine speed is influenced by changes in compressor load. The diesel engine used during testing was speed regulated by a mechanical governor. When the compressor is unloaded, the engine speed increases, which typically results in higher fuel consumption. By repeating the testing with an electronically governed engine, the data will likely show better engine speed control under varying compressor loads. This type of engine control can result in more stable speeds and lower fuel consumption during transient loading events.

In Figure 14, refrigerant discharge pressure increases with increasing compressor load. This trend is expected; however, it is unclear why the 50% compressor load case results in the highest peak-to-peak discharge pressure measurement. The interaction between discharge pressure and engine load can be used to validate TRU control algorithms, which often use discharge pressure readings as an input. TRU components such as condenser fans and system cutouts switches are controlled using discharge pressure measurement, so understanding the interaction between torque and discharge pressure can be beneficial for algorithm and system design.
From the measurement results above, it is clear that the compressor loading and unloading affects torque behavior. Understanding the different compressor load cases and the resulting torque measurements allows for more meaningful engineering analysis. The torque measurement data above can be used to calculate maximum and average torque for different load cases. These values can then be used as inputs for stress/strain analysis and life predictions for mechanical coupling and compressor components. The data can also be used as an input for the harmonic analysis of different components, which connect the diesel engine to the open drive compressor.

6. CONCLUSION

In the TRU application, the mechanical slip ring device was found to be more effective than the telemetry device for collecting torque signature data. Using the torque measurement data, engineering calculations and algorithm design can be improved. The torque signature also helps ensure that the TRU control strategy will not violate the engine’s regulatory power limitations during transient events. It is recommended to repeat the data collection using an electronically governed engine. Such testing may uncover the benefits of improved speed control, as it relates to engine power limits and TRU control algorithms.

REFERENCES


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