A non-intrusive, vibration based, automated analysis supports compression equipment efficiently & economically

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Summary

Automated analysis of reciprocating machinery's condition & performance can follow different approaches, such as physics based mechanistic model analysis or empirical models developed from historical operational data. In this article, a hybrid model consisting of both physics based model and empirical model is proposed. This strategy has been successfully implemented on a Cooper Bessemer GMWA-10 integral engine compressor at a Williams gas-compression station. This article describes instrumentation, data analysis and identifying a defective fuel-valve. A mis-combustion event is detected based on exhaust blow-down data analysis.

Introduction

Automated analyses of reciprocating machinery's condition & performance can follow different approaches, such as:

A physics based mechanistic model
Engine and compressor physics are described by a mathematical model and run on a server in parallel with the actual machine, also called a **'physics based digital twin'**. For the 'digital twin', detailed '**machine specific**' knowledge is required.

An empirical model developed from historical machine operational data
machine behavior is referenced against historical readings (same machine, same conditions) in order to find deviations. A **nominal or fault** data-model, against which actual readings are benchmarked, is also called '**historical twin'**. The 'historical twin' is '**machine agnostic**' and can be utilized on any type of machinery without requiring prior knowledge of working principles.

This article proposes a hybrid model, with both a machine agnostic component <u>and</u> a machine specific component.

Nominal model:

Shortly after start-up of a healthy integral engine and compressor, crank angle referenced, nominal models of vibration waveforms are generated. After a few weeks of operation, the engine and compressor set has run through all speed-load points and the automated nominal, vibration waveform based, model generation is complete. The crank angle referenced vibration waveforms will continue to be correlated with existing nominal models.

At certain points in time, the waveforms generated from new data may not show any significant correlation to the existing nominal models. If this is the case, then a configurable minimum number of similar waveforms will be used by the analytics to generate a 'new model'. For this new-model generation event, an alert will be generated. At this point, compressor operator or the engineer will review the newly generated model and decide if it is a new operating nominal or it is an abnormality pointing to a faulty part. If it is a faulty part, the event is labeled with a fault-name. Up to this point the process remains machine agnostic.

Hybrid model:

Based upon a detailed understanding of the way certain faults have an impact on machinery vibrations (timing, amplitude, frequency-content), further nominal fault models can be *composed.* In addition to the above machine agnostic nominal processes, machine specific models (applications) can be added.

Integral engine-compressor Instrumentation and Data Acquisition set-up

For the development and validation of the analytics described in this article, following measurement instruments were installed on an integral Cooper Bessemer GMWA-10 engine-compressor at the Williams Station 45 in Ragley, LA:

1. 100mV/g accelerometers[1] installed on all 10 power cylinders & all 3 crossheads (figures 1,2)
2. A magnetic pick-up installed on the fly-wheel to generate 1 reset-pulse per revolution

Figure 1: accelerometer installed on combustion cylinder

[1] The frequency response curve is flat between around 3Hz - 10'000Hz

All wires routed to a single data acquisition enclosure (figure 3), which samples all accelerometer signals at 60kHz and offloads raw waveforms to the data analytics web-portal environment for further processing. Accelerometers are installed on glue pads on the compressor with a two component structural adhesive. Generated ‘historical twins’ can be (re)used on other compressor sets of the same model as long as the accelerometer locations and installation method are identical.

Figure 2: accelerometer installed on crosshead

Installation and commissioning of the instrumentation and the data acquisition (DAQ) panel is quick and easy.
Additionally, Williams also set-up an interface to push other engine and compressor data being collected by their Pi system into the Cooper Performance Management System (CPMS) server.

Figure 3: data acquisition module

Raw waveform analysis

Typical raw waveforms measured on the combustion-cylinders are shown in figure 4. They clearly show events like combustion (E), ring-action (D), exhaust-blowdown (A), crosstalk exhaust-blowdown from cylinder across (B) and fuel-valve closing (C).

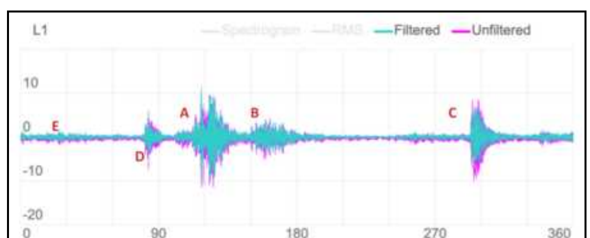

Figure 4: typical waveform combustion cylinder

These raw waveforms are uploaded to the CPMS portal continuously in real-time, where they are displayed as waterfall graphs, which are synchronized with time-based graphics on the left and crank-angle referenced individual waveforms on the right (figure 5).

Users can select individual waveforms by clicking in the time-based graphs on the left or in the waterfall diagram in the middle. Individual waveforms can be further analyzed in detail on the right-side of the portal with several analysis tools[2].

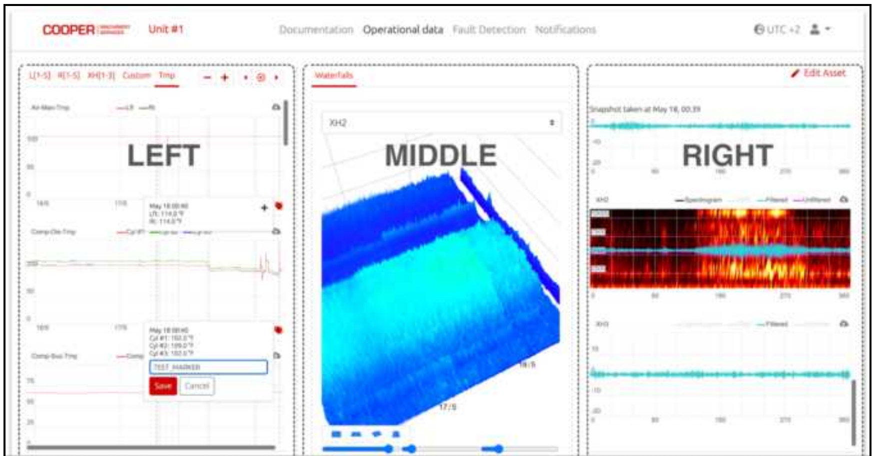

Figure 5: overview screen data-analytics portal

High to low resolution waveforms and model-generation

As a first step, high-resolution waveforms are compressed into low-resolution waveforms[3] (figure 6). This allows fast statistical processing of a high number of waveforms and also allows for these analytics to be performed 'at the edge'[4].

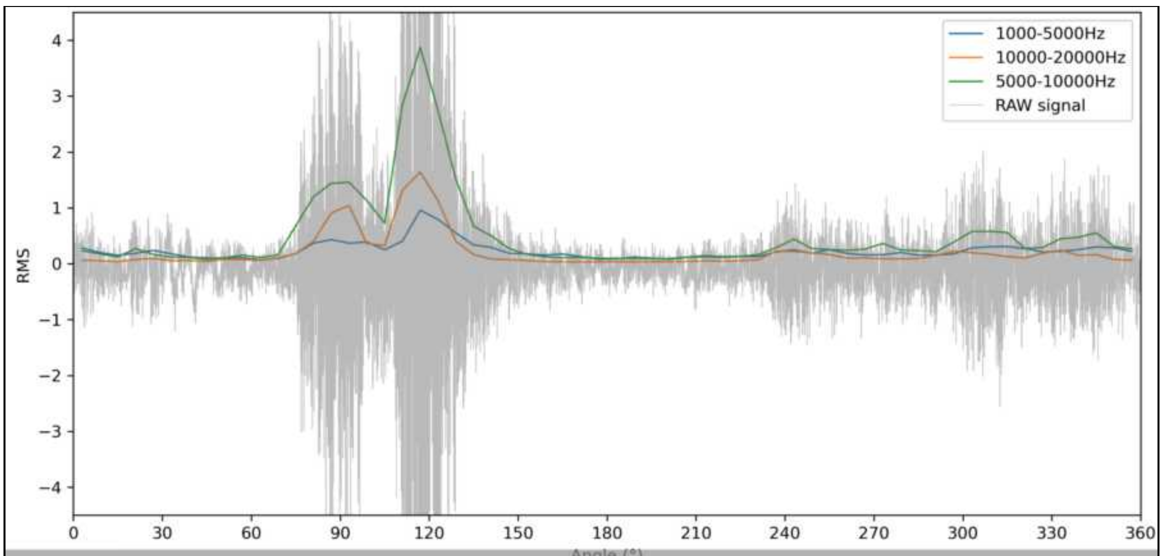

Figure 6: high- and low-resolution vibrationwaveforms

Low resolution waveforms have been generated for 3 frequency bands (1kHz-5kHz & 5kHz-10kHz & 10kHz-20kHz). The last frequency band falls outside the 3dB area of the frequency response curve and is regarded as 'experimental'. In this article, we only use the first two bands.

[2] These include e.g. spectrography, band-pass filtering and resynthesizing vibration waveform into sound
[3] For this field-test, we have used 60 waveform segments of 6° each
[4] In a next product iteration, described analytics will run on a Nordic nRF52840, 'at the edge' in a small form-factor

After low resolution waveforms have been generated, similar waveforms are combined into ‘models’, which initially describe nominal operations and are later used for automated fault-finding.
A ‘model’ is composed of a number of similar waveforms and includes a 90% confidence interval.
On the GMWA-10, nominal operation of the crosshead 1 was described by 1 model generated in the 1kHz-5kHz range and 3 models describing the 5kHz-10kHz range (figure 7).

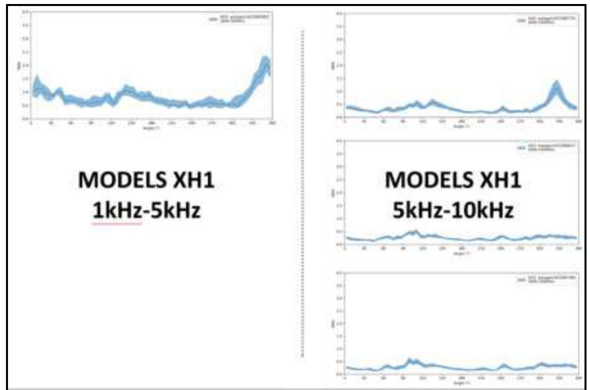

Figure 7: nominal models for crosshead 1

Automated alert on the GMWA-10, cylinder R3

In mid July, 2021, an alert was generated for cylinder R3 in the 5kHz - 10kHz range (figure 8), indicating the automated generation of a new (historical) ‘model’. The alert was generated as the analytics could not find a strong correlation between the newly measured waveform and the existing nominal models for R3.

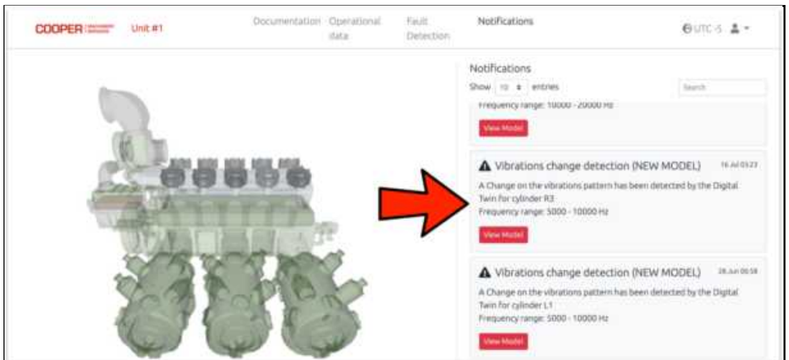

Figure 8: receiving alert new model generation R3

Upon further examination of the waveform data as shown in the chart below, it was determined that a new high peak[5] occurred at around 275° crank-angle, at the point where the fuel-valve closes (figures 9, 10).

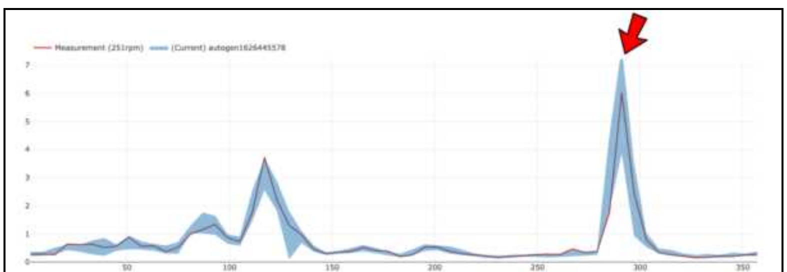
Figure 9: newly generated model R3

When reviewing the mis-combustion graphs (figure 11, as described in the next paragraph), it also showed a significant increase of mis-combustion at the same moment in time.

[5] Both spectrogram and audio revealed a high-pitched sound which indicates metal-to-metal impact

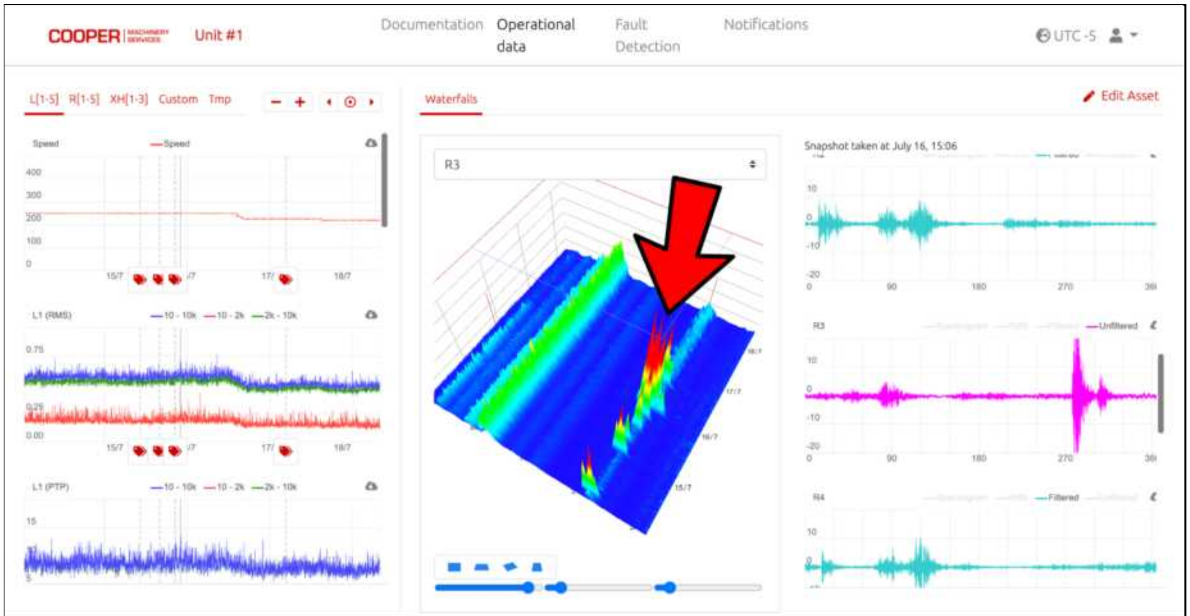

Figure 10: R3 waterfall in web-portal

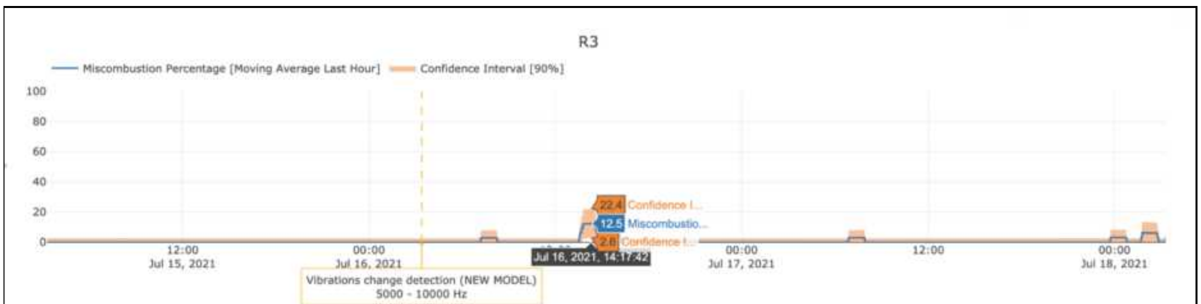

Figure 11: miscombustion on cylinder R3

Williams operation crew further investigated the fuel-valve on R3 and found a soft lifter was to have intermittent issues. Replacement parts were ordered for repair of this valve. Due to the early identification and notification, unplanned downtime was avoided and replacement parts could be ordered while the machine was still in operation.

Permanent mis-combustion analysis

Besides automated model generation based on engine and compressor operational data as described in the previous section, we have also developed a model describing a fault case (machine specific). This is based on our understanding of how nominal and faulty engine/compressor operations affect the measured waveforms. This methodology can be expanded to capture additional operational knowledge (i.e., faulty ring-action, fuel-valve and liner-scoring, etc.).

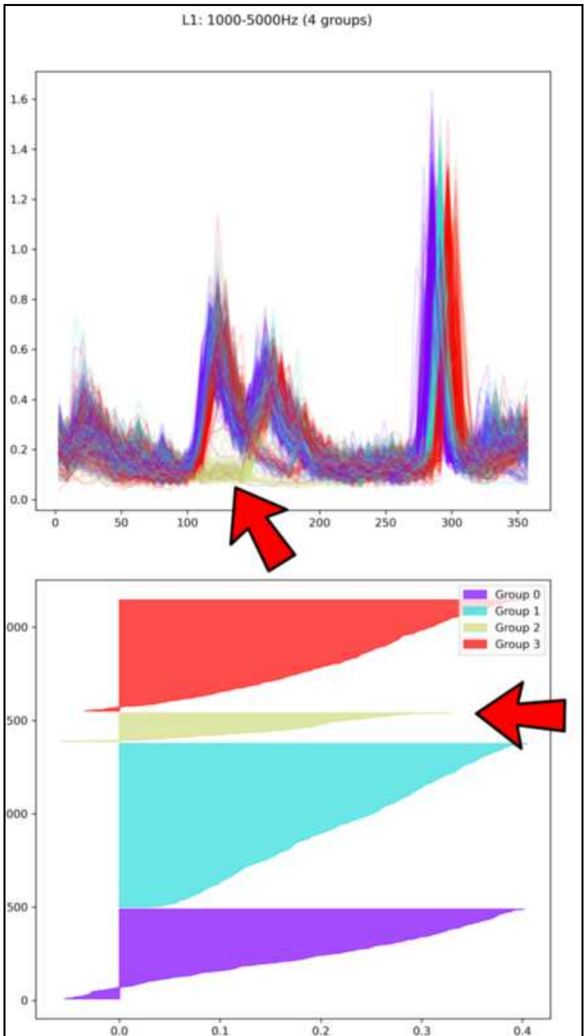

figure 12: selecting miscombustion waveforms using k-sorting algorithm for 'manual' creation of fault-model

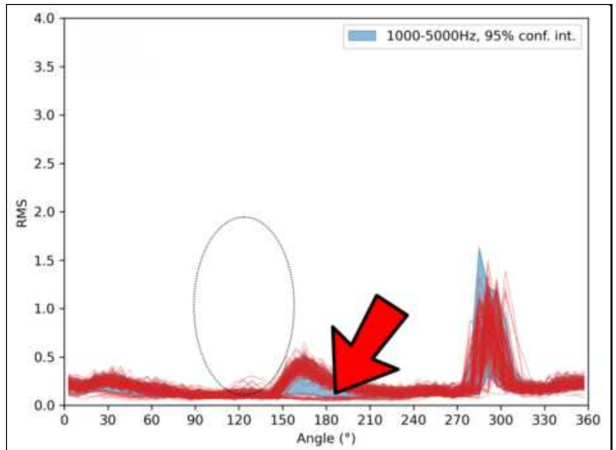

Figure 13: Model created for miscombustion L1

Figure 14: miscombustion graphs in web-portal

At the location where the accelerometers were installed on the GMWA-10, combustion noise was lightly audible. However, the noise caused by the exhaust gasses being pushed out of the combustion cylinder (exhaust blowdown) were *clearly* audible. Additionally, crosstalk from the opposing cylinder exhaust blowdown was also clearly visible in the measured waveforms[6]. Based upon a data set of around 4500 low-resolution waveforms[7] and using the k-sorting algorithm, we sorted out all mis-combustion waveforms in figure 12 for all combustion-cylinders (the arrow points to the waveforms which don't show an exhaust-blowdown for L1).

[6] This opens-up the possibility to do combustion analysis of two opposing combustion cylinders with only 1 single accelerometer drastically reducing material cost and time required for the installation
[7] Frequency range of 1kHz - 5kHz

Based upon this sub-set, we created mis-combustion models for every cylinder (example for L1 in figure 13).
For every newly measured waveform, correlation against ‘nominal’ and correlation against the mis-combustion models is calculated.
The percentage of mis-combustion is calculated and trended together with a 95% confidence interval, which is based upon the amount of samples vs the total quantity of revolutions[8].

In order to validate this approach, the reported percentage of mis-combustion was checked against the measured engine torque at that point. The relationships found between percentage mis-combustion and engine torque were found to be as expected (figure 14).

Conclusions

The presented (machine agnostic) vibration-based, non-intrusive, analysis has proven to be an efficient and effective tool to support operation and maintenance of gas-compression equipment.
If newly measured waveforms do not show a sufficient correlation with a compressor nominal model, new fault models are generated and a notification is sent. This process has been illustrated and validated by the early identification of a failing fuel valve, which required service.
Machinery knowledge can be used to compose machine specific fault models, which allow continuous trending of machine conditions. This has been illustrated by trending the percentage of mis-combustion on a Cooper GMWA-10.

As a next step we envision further generation of fault models related to additional events such as ring-action, scoring. We also plan to develop distribution of nominal and fault models across a larger fleet of GMWA-10 compressors in order to prove that generated machine specific fault models can be reused across other same model machines.

[8] Which can be calculated based upon the compressor RPM