HUMS2025 Data Challenge Result Summary

Team Name: GPMS

Eric Bechhoefer, Changik Cho

GPMS International Inc, 93 Pilgrim Park Rd, Waterbury, VT

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1. Summary of Findings

- It was hypothesized that the gearbox crack resulted from high cycle fatigue, which implies high torque loading. The highest torque on the gearbox will be the ring gear/planet interaction. The analysis was focused on this interaction.
- If true, the crack reduces the stiffness of the ring gear, resulting in nonsinusoidal waveforms associated with the ring gear modulated by the planets. As this is a breathing crack, impact resonance is expected to be modulated by the planets. Any indicator should be sensitive to torque.
- Two analyses were conducted. The first used the ring gear's amplitude modulate (AM) RMS, normalized for the torque effect (e.g., dCI/dTorque). The second analysis used the envelope from 1 to 3 kHz, where the condition indicator was the spectrum energy associated with the gear mesh frequency corrected by asymmetry (98 vs. 99 teeth, see ref 1), again corrected by torque. While the AM RMS trended from the first acquisition, the effect of torque began to increase by acquisition 35 (Day004_20240320_152738). This was observed on all four channels. Similarly, for the envelop analysis, a positive dCI/dTorque and trend was observed by acquisition 35.
- The best channels for the AM RMS and the envelop analysis were 1, 3, and 4.

2. Description of Analysis Methods

The AM RMS is based on the time synchronous average (TSA), where the ratio from the tachometer to the mast: Input Pinion/Bevel Gear x 1/(1 + Ring Gear/Sun Gear), with the input pinion, is 19T, bevel gear is 71T, ring gear is 99T, and the sun gear is 27T, giving a ratio of 0.057344064 from the input shaft. However, because of the asymmetry of the sideband modulation, the tooth meshing frequency for fault extraction was taken at 98 vs. 99. The AM analysis is calculated as the absolute value of the Hilbert transform of the bandpass TSA. The bandpass filter was, in the order domain, 74 to 122.

An envelope analysis detected gearbox case resonance due to a breathing crack. The modulation frequency (resonance of the gearbox) was 3kHz, with a bandwidth of 1kHz. That is, the acceleration data was mixed with an analytic 3kHz signal. This was then low-passed filtered, and then the absolute value of the resulting analytic signal was taken to derive the envelope. The spectrum was then taken with the condition indicator being the spectrum energy of the asymmetric mesh frequency of 0.057344064 x 98 x 99.99Hz (input shaft rate), or approximately 562 Hz.

The effect of torque and the trended algorithm used a linear model where: $CIf(i) = [1 + time(i) + dTorque \times Torque(i)] \times CI(i)$, where $CIf(i)$ is the filtered CI, and $CI(i)$ was AM RMS or Envelope Energy at time i. The analysis window used 20-time indexes (e.g., idx = i-20:i) and was solved using least squares.

3. Key Fault Characteristics for Early Detection

It was assumed that the gearbox casing crack resulted from high cycle fatigue due to ring/planet gear mesh loading. Features associated with the ring/planet rate (e.g., gear mesh) should increase with time and be sensitive to torque. Additionally, we assumed that the crack would excite resonance in the gearbox case, which would be modulated by the gear mesh and the passage of the planets on the ring gear. As the planet/ring gear rate is 23 Hz, and the gear mesh is 562 Hz, we expect to see these features (gear mesh 562Hz +/- 23 Hz sideband) in the envelop spectrum, as seen in Figure 1.

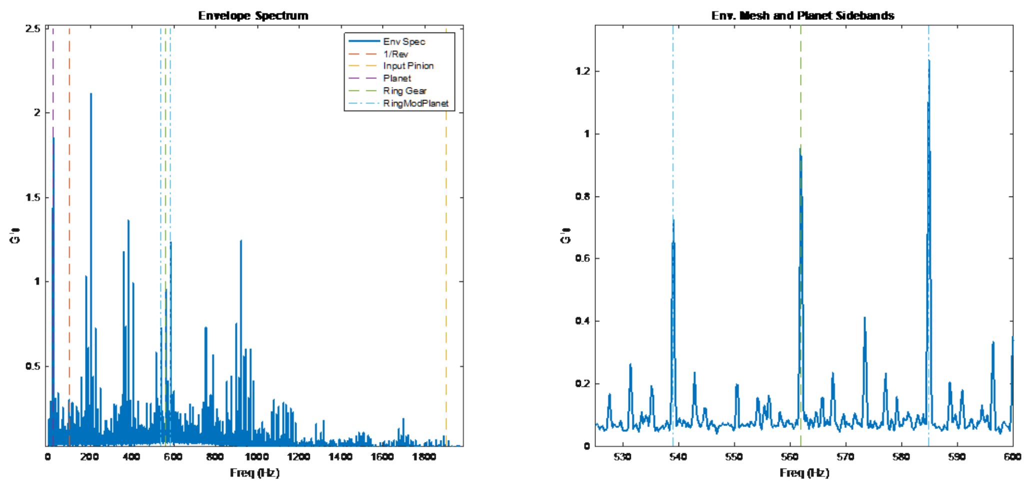

Figure 1 Example of the Envelop Spectrum vs. Ring/Planet Frequencies

Usually, data associated with a pre-damaged state are used to baseline or take statistics of nominal data. This would allow a threshold to be set based on some probability of false alarm. However, we observed CI trends for a number of TSA-based analyses (where AM RMS was chosen) and the envelop analysis starting just the first few acquisitions. We also assumed that the crack growth and resulting CIs would initially be sensitive to torque. Higher torque should deform the gearbox case/larger impact from a breathing crack, resulting in a higher CI value. As such, we normalized by torque using a linear state observer. The torque effect on the CI (e.g., dCI/dTorque) increased before 35 acquisitions.

4. Fault Progression Trending Curve

Each CI plot (AM RMS and Envelope Energy) is normalized by: (CI – min(CI)/(max(CI)-min(CI)) so that they have a common scale for viewing. Additionally, each plot shows the trended (normalized by torque) value and the trended CI at acquisition 35, when most of the dCI/dTorque indicators are trending positive and significant.

Figure 2 shows the AM RMS trend for all four channels, where channels 1 and 4 have the best trend. Figure 3 is the effect of torque on AM RMS. The most significant impact of torque on the CI is seen in channel 2. Figure 4 plots the envelop energy for the asymmetric gear mesh energy. Note that channel 2 is nearly a linear trend when normalized for torque. As shown in Figure 5, the effect of torque on channel 2 is negative.

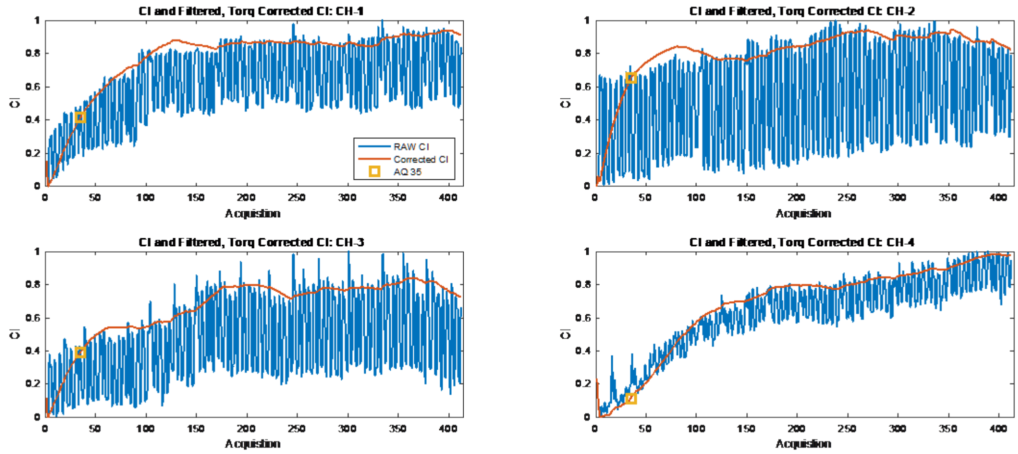

Figure 2 TSA AM RMS Trend

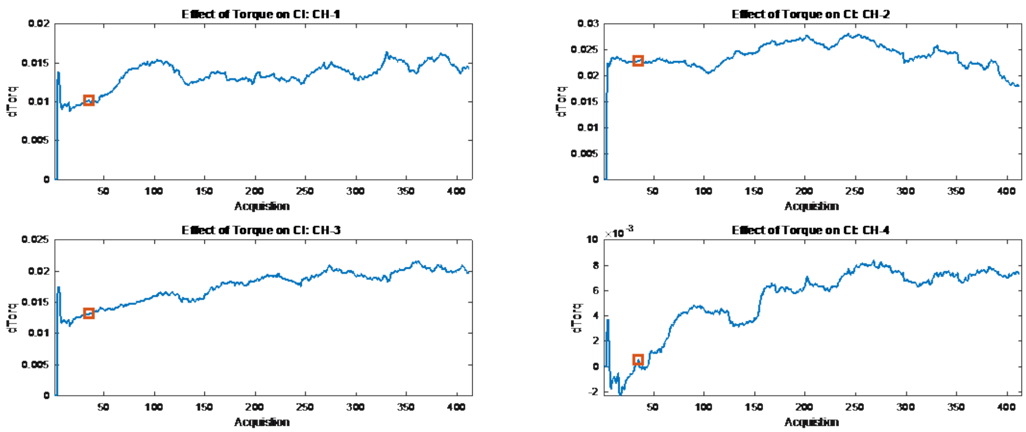

Figure 3 dCI/dTorque for AM RMS

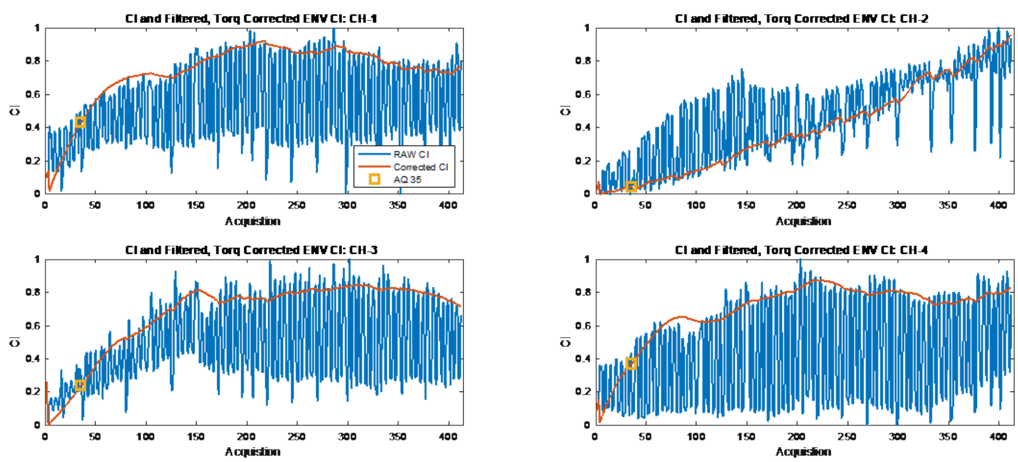

Figure 4 Envelop Energy at 3 kHz for the Ring Mesh Frequency

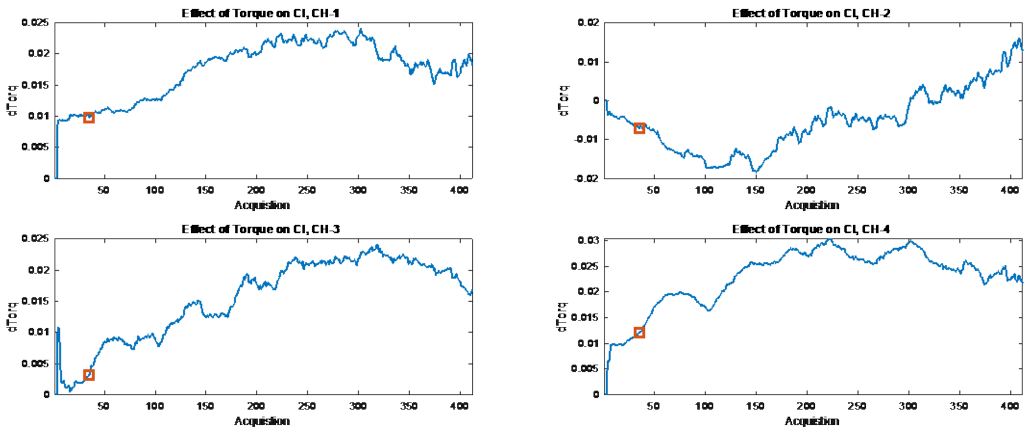

Figure 5 dCI/dTorque of the Envelope Energy of the Ring Gear Mesh

5. Supplementary Information

Twenty different analyses based on the TSA were tested, including:

- Residual RMS, Kurtosis, and Crest factor
- Energy Ratio, Energy Operator Kurtosis, and Crest Factor
- Figure of Merit 0, Sideband Lifting Factor and G2 analysis
- Narrowband Kurtosis and Crest Factor
- AM RMS, Kurtosis, Peak to Peak, and Crest Factor
- FM RMS and Kurtosis
- Gear Mesh Energy (98 vs. 99 for Ring Gear)
- AM Residual RMS and Kurtosis

Of these, Residual RMS, Narrowband Crest Factor, Gear Mesh Energy, and AM Crest Factor all captured features with a strong positive trend. For the envelope analysis, other CIs were based on the Input Shaft rate, Input Pinon Rate, planet modulation rate, the envelope's kurtosis, and the envelope energy sum. Of these, only the sum of energies proved to be trendable.

As no nominal data was observed, statistics could not be developed to facilitate data fusion or convert the CI to an HI (e.g., developing a maintenance recommendation).

Reference:

1) McFadden, P.D., Smith, J.D., “An Explication for the Asymmetry of the Modulation Sidebands about the Tooth Mesh Frequency in Epicyclic Gear Vibration, Proc Intsto Mech Engs Vol 199, No C1, 1985.