



HUMS2023 Data Challenge Result Submission

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Publishable: Yes

1. Summary of Findings

- The root crack is related to the harmonics of the Planet Gear, and in specific to the 2nd harmonic (2xPG) as the root crack teeth mesh twice with each revolution, once on the ring gear and once on the sun gear.
- The carrier component is removed from the signal with synchronous averaging, to enhance the signal to noise ratio of the planet gear. The envelope spectrum then exhibits the planet gear modulations, and when the 2nd harmonic is consistently above the threshold, the root crack is considered detected. With this method, the damage is detected in signal #309 for the accelerometer RR4, and in signal #313 for the accelerometer RL3.
- Using the information of 3 accelerometers instead of each one separated by averaging the envelopes enhances the signal to noise ratio. The 2nd harmonic of the Planet Gear is consistently detected above the threshold at signal #294.
- Tracking the amplitude of the 2nd harmonic of the Planet Gear after the early detection (at signal #294) provide a trending curve for prognostics purpose, showing an increasing monotonic exponential curve until the end of the dataset and the breakdown of the gear.

Table 1 Summary of Analysis Results

#	Detection & Trending	Data file name/number	Comments
1	Consistent detection on at least one signal channel; i.e. the fault indicators remain consistently above the threshold.	Day024_Hunting_SSA_20211216_142217 Signal #309	Residual of Envelope Spectrum of accelerometer RR4 (Figure 2)
2	Confirmed detection on at least two signal channels; i.e. the fault indicators remain consistently above the threshold.	Day024_Hunting_SSA_20211216_144133 Signal #313	Residual of Envelope Spectrum of accelerometer RL3 (Figure 3)

3	Clear multi-channel indication of the characteristic fault features; i.e. faulty planet gear meshing with both the ring and sun gears.	Day024_Hunting_SSA_20211216_132200 Signal #294	Averaged Residual of Envelope Spectrum of all 3 accelerometers RF2, RL3 and RR4, Alarm Rate (Figure 4)
4	Confirmed trend of fault progression; i.e. a consistent increasing trend started from which file number/name.	Day024_Hunting_SSA_20211216_132200 Signal #294	Averaged Residual of Envelope Spectrum of all 3 accelerometers RF2, RL3 and RR4, Alarm Rate (Figure 4)
5	Confirmed trend of accelerated fault progression; i.e. a consistent exponential increasing trend started from which file number/name	Day024_Hunting_SSA_20211216_142217 Signal #309	Averaged Residual of Envelope Spectrum of all 3 accelerometers RF2, RL3 and RR4, Detection Rate (Figure 4)

2. Analysis Methods

The method consists in subtracting the Synchronous Average of the Carrier (SAC) from the original provided Synchronous Average of Hunting Tooth (SAHT). This results in a Residual signal (RPG) retaining the Planet Gear information, which rotates at 16.23 rps. To access the modulation signature of the planet gear, the envelope spectrum is extracted from the residual RPG signal via Hilbert transform followed by the Fast Fourier Transform.

The characteristic frequency of interest related to the planet gear is 16.23 Hz and its harmonics, which is the rotation speed, or in other words, the rate at which the pair of teeth with the root crack meshes with the ring gear. Namely, the most important harmonic is the 2nd harmonic of the planet gear speed ($2 \times 16.23 \text{ Hz}$), because the root cracked teeth meshes on both sides, once with the ring gear, and half rotation later with the sun gear. Analyzing the envelope spectrum of the RPG signal, detection of the amplitude of the 2nd harmonic of the planet gear speed above the background noise level and higher than the other harmonics indicates a fault on the planet gear.

The methodology described until now is applied to one single accelerometer; however the planet gear is rotating away from one accelerometer and closer to another accelerometer, and usually the closer the accelerometer is to the source, the better the signal to noise ratio is. As such, using the information of all 3 accelerometers on top (RF2, RL3 and RR4) by summing the 3 envelope signals before extracting will improve the robustness of the method. A schematic describing of this method, denominated as Average of the Residual Envelopes (ARE) is shown in the Figure 1.

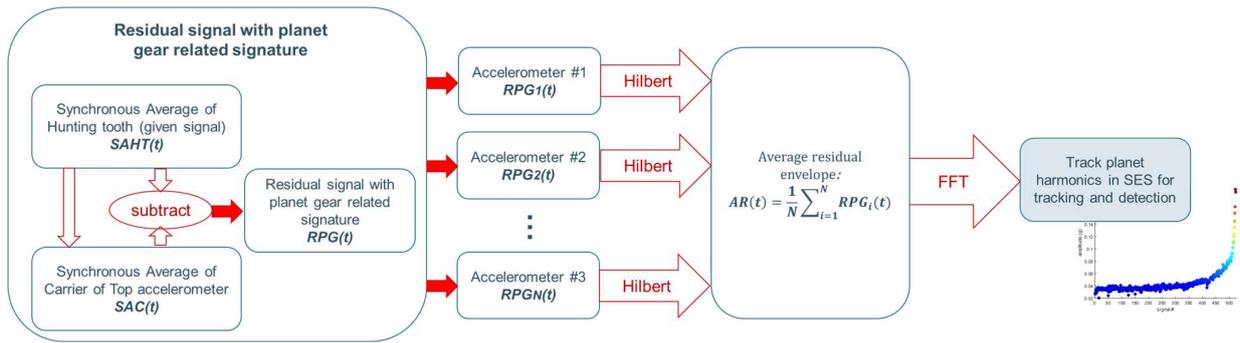


Figure 1: Average of the Residual Envelopes (ARE) for root crack diagnosis and tracking on planet gear

3. Illustrating Figures

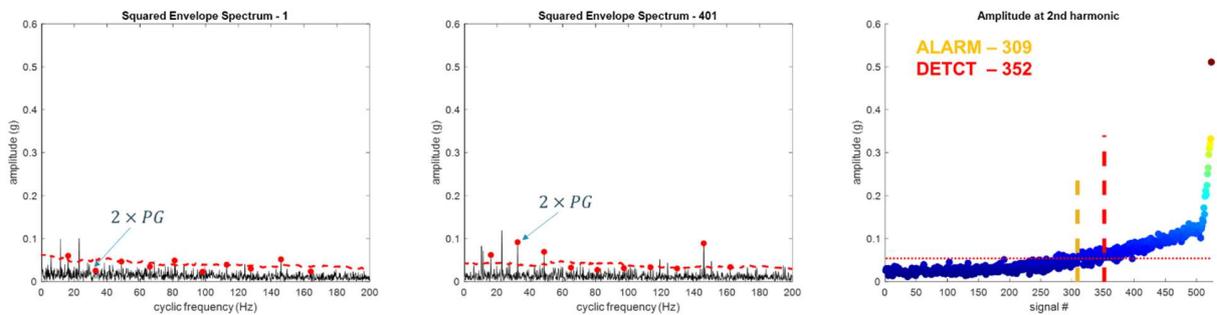


Figure 2: Residual Envelopes Spectra of accelerometer RR4 at (left) the beginning of the dataset and (middle) and at late measurement #401. (right) Tracking the amplitude of the 2nd harmonic of the Planet Gear as an indicator.

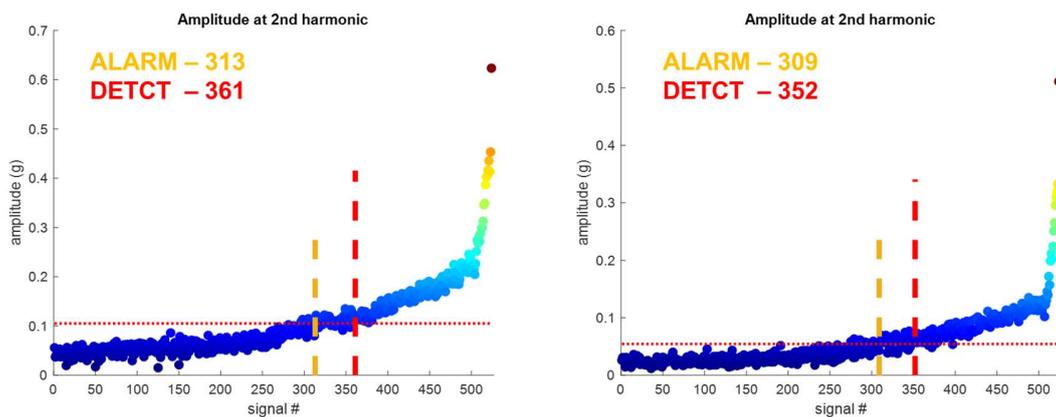


Figure 3: Alarm rate and detection rate of Residual Envelope Spectra by tracking the amplitude of the 2nd harmonic of the Planet Gear as an indicator for: (left) accelerometer RL3, (right) accelerometer RR4

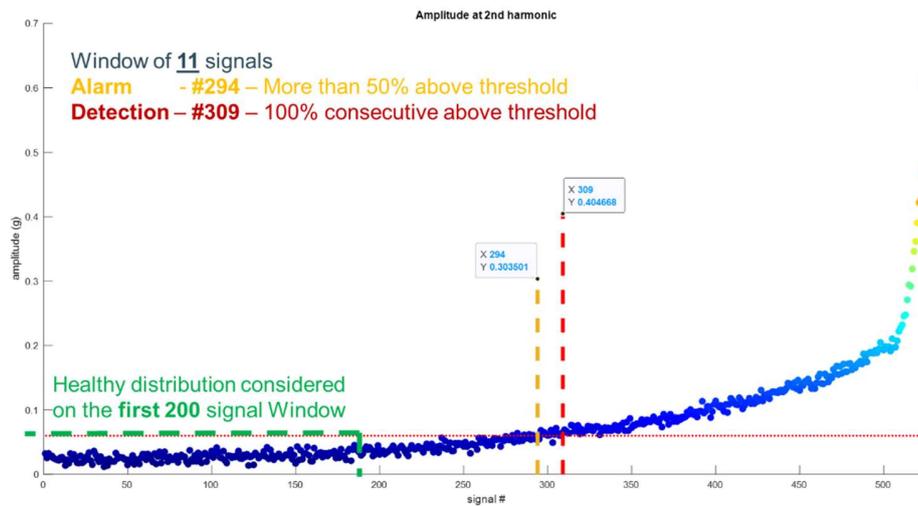


Figure 4: Alarm rate and detection rate of the Averaged Residual Envelope Spectra by tracking the amplitude of the 2nd harmonic of the Planet Gear as an indicator.

4. Characteristic Fault Signatures of Early Detection

The characteristic fault signature for the planet gear rim crack should reflect the fact that the planet teeth affected by the faulty portion would come into mesh with both the ring gear and the sun gear teeth. As such, for detecting the damage is done by detection of the amplitude 2nd harmonics of the planet gear frequency on the envelope spectrum consistently above the noise level.

The 2nd harmonics of the PG remains at the noise in the first acquired signals. The noise level on the envelope spectrum is defined as 6 times the Median Absolute Deviation above the Median. The window of the first 200 signals is used to define the healthy threshold. When the amplitude 2xPG is consistently detected above the threshold, the damage in the planet gear is considered detected. To be statistically relevant, a moving window of 11 signals is applied, and if 50% of the signals show a value above the threshold the damage indicates the presence of the damage as an ALARM. In case 100% of the signals, or in other words all 11 signals in the window, show a value above the threshold, the damage is defined as DETECTED.

In the previously shown Figure 4 it can be seen that the ALARM indicates the planet gear damage at signal #294, and the DETECTION occurs at signal #309, using the average of the residual envelopes method of all three accelerometers, as described in Figure 1.

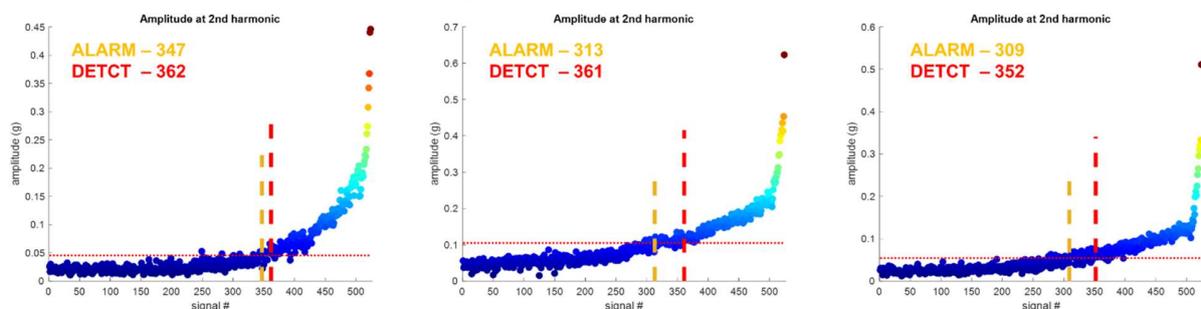


Figure 5. Characteristic fault signal of the earliest detection by channel (left) RF2, (middle) RL3, (right) RR4.

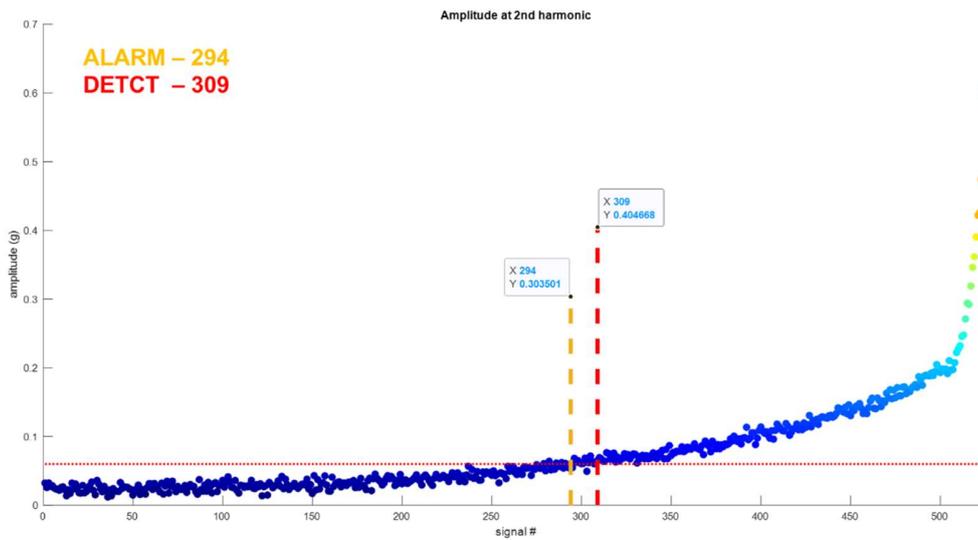


Figure 6. Characteristic fault signal of the earliest detection by ARE method using the 3 accelerometer signals

5. Fault Progression Trending Curve

This curve will be compared with the estimated crack growth curve produced by DSTG's fractography analysis.

The trending curve for tracking the fault progression is the same indicator described in the previous section, as the amplitude of the 2xPG by the ARE method using the 3 accelerometers after the ALARM signal indicating the early detection. The trending curve starts at signal #294 and can be seen in Fig. 7. The curve shows to be monotonic and continuously increasing from #signal 294 until the last signal #526. The rate of increase shows a small exponential coefficient until signal #505 at which rate of the increasing trend grows to a higher exponential coefficient until the last signal #526.

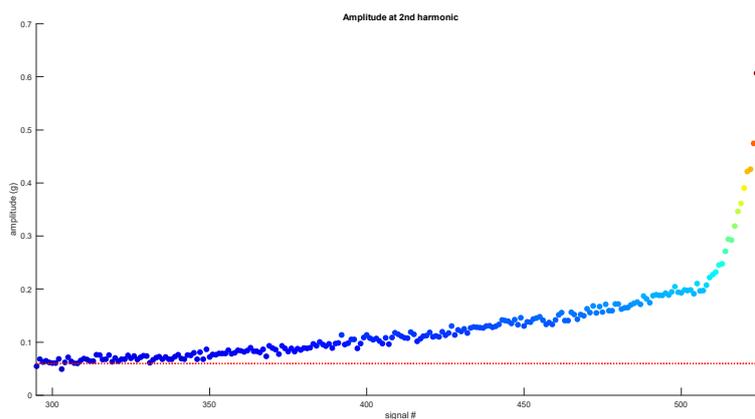


Figure 7. The trending curve for the planet gear fault progression indicating where the fault indicator started to increase consistently and where the fault progression started to accelerate, using the ARE method and 3 accelerometers at 2xPG

The harmonics of the Planet Gear (PG) besides the 2nd are also damage related, thus tracking 10 harmonics of the PG also provide a good trending curve, as seen in Figure 8. The ALARM rate occurs at a later stage in this case, in signal #359, but the exponential trending is similar to the previous mentioned curve.

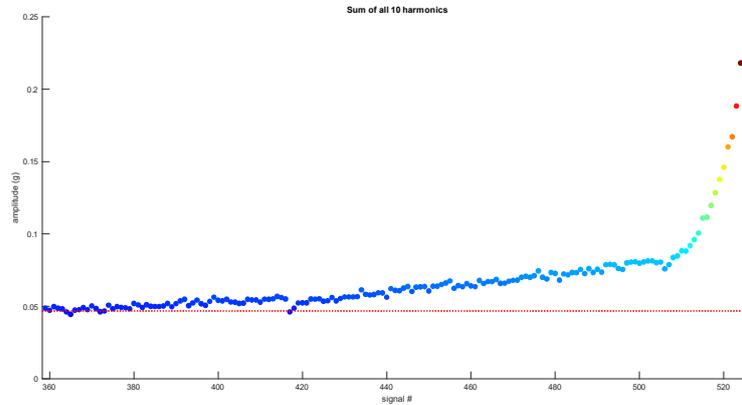


Figure 8. The trending curve for the planet gear fault progression indicating where the fault indicator started to increase consistently and where the fault progression started to accelerate, using the ARE method and 3 accelerometers at the 10 harmonics of PG

6. Description of Analysis Methods

Description of fault detection method

Extract the synchronous average at the carrier speed frequency and subtract it from the synchronous average of the hunting tooth. Compute this residual signal and its Hilbert transform (envelope signal) for all 3 accelerometers mounted on top of the gearbox. Average the 3 envelopes and apply the Fast Fourier transform to obtain the envelope Spectrum. Pick the peak at the 2nd harmonic of the planet gear frequency (2xPG) as an indicator. Apply a threshold based on the first 200 signals/indicators as 6 times the Median Absolute Deviation above the median. Obtain a moving window of 11 consecutive signals. When 50% of the indicators inside the moving window are above the threshold (ALARM), the fault is considered detected.

Description of fault trending method

Continue tracking the indicator described in the previous subsection, amplitude at 2xPG of the ARE method, which is also detailed in the scheme in Figure 1. The trending curve corresponds to the exponential curve of the indicators starting from the early detection signal (ALARM).