HUMS2023 Data Challenge Result Submission

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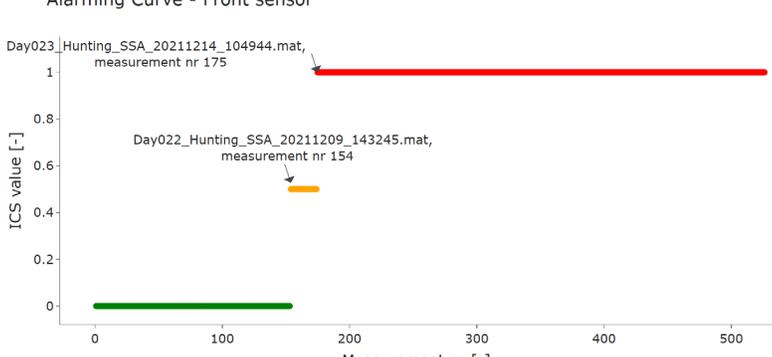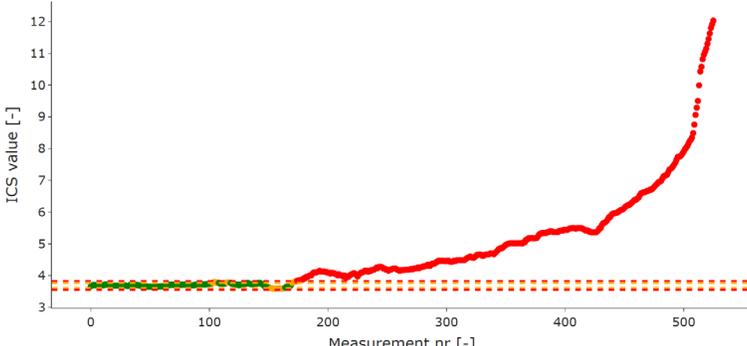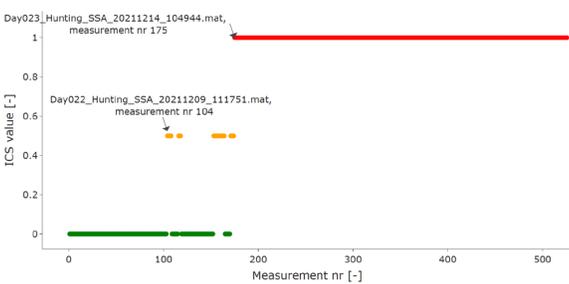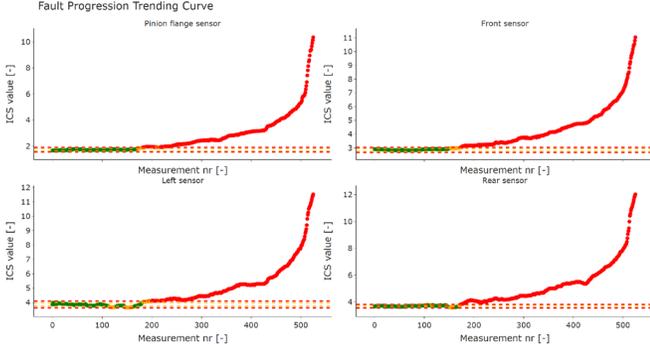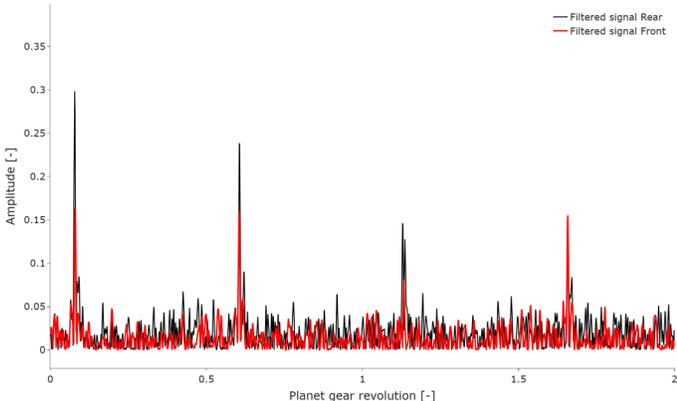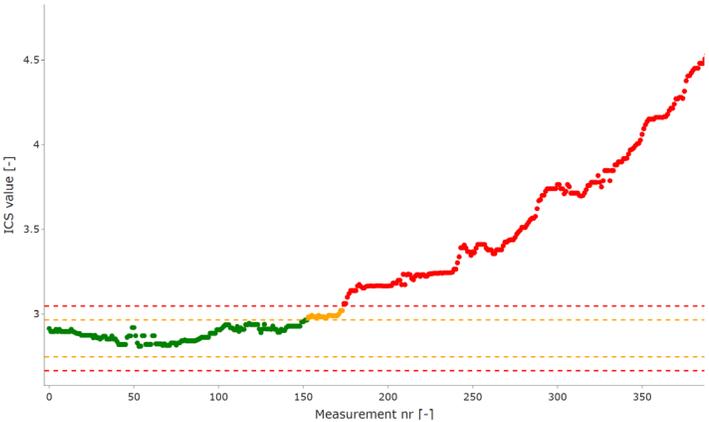
Publishable: Yes

1. Summary of Findings

While initial attempts to optimally track the gear degradation focused on applying conventional planetary gear approaches (i.e. separating windowed planet contributions whilst leveraging the presence of multiple sensors), the final approach doesn't use this approach. Instead, the proposed approach focuses solely on trying to optimize a filter that extracts the cyclostationary signature of the rim crack once it comes into the ring/sun gear mesh. Using this filtering method, a clear, periodic, impulse train can be observed at the planet rotation frequency, simultaneously in all 4 sensors, with the input pinion sensor being the least sensitive to the fault. If the first 100 measurements are used to define a baseline model of so-called ICS (Indicators of CycloStationarity) values, a clear increase is observed starting at measurement number 175 for the front and rear sensor. Earlier measurements could potentially already be considered as crossing warning thresholds. Interestingly, already the first measurements of the front, left, and rear sensors showcase both planet gear-related impulses and above-normal ICS values. Given the identical impulse structure on the different sensors after filtering, the earliest detection point could be measurement nr 1, however, there is no healthy measurement available so this is difficult to determine with certainty.

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.	Warning Alarm level: - File nr 154, Day022_Hunting_SSA_20211209_143245.mat Critical Alarm level: -File nr 175, Day023_Hunting_SSA_20211214_104944.mat	**Method of detection**: Data-adaptive ICS filter method. Produces both filtered fault signal and fault indicator. Details in section 2. **Figure of reference #1**: ICS indicator trend on <u>Front sensor</u> along with warning and alarm thresholds defined by Tukey's method on first 100 measurements. **Figure of reference #2**: Alarm trend for <u>front sensor</u>

Alarming Curve - Front sensor

2	Confirmed detection on at least two signal channels; i.e. the fault indicators remain consistently above the threshold.	Warning Alarm level (consistent, >5 consecutive warnings): - File nr 153, Day022_Hunting_SSA _20211209_142945.mat Critical Alarm level: -File nr 175, Day023_Hunting_SSA_ 20211214_104944.mat	**Method of detection**: Data-adaptive ICS filter method. **Figure of reference #1**: ICS indicator trend on <u>rear sensor</u> along with warning and alarm thresholds defined by Tukey's method on first 100 measurements. Fault Progression Trending Curve - Rear **Figure of reference #2**: Alarm trend for <u>rear sensor</u> Alarming Curve - Rear sensor
3	Clear multi-channel indication of the characteristic fault features; i.e. faulty planet gear meshing with both the ring and sun gears.	Critical Alarm level: -File nr 175, Day023_Hunting_SSA_ 20211214_104944.mat	**Method of detection**: Data-adaptive ICS filter method. **Figure of reference #1**: ICS indicator trends on all 4 sensors. Both rear and front sensor cross critical alarm at file nr 175. Fault Progression Trending Curve

Note: table columns above correspond to row number, detection criteria description, alarm level file references, and method of detection with figures.

			Figure of reference #2: Zoom of absolute value of ICS-filtered signal for first 2 planet gear revolutions, with 2 impulses per planet revolution. A noiser version of this impulse structure can also already be observed for the first measurements after ICS-filtering. measurement nr 175, Day023_Hunting_SSA_20211214_104944.mat
4	Confirmed trend of fault progression; i.e. a consistent increasing trend started from which file number/name.	Critical Alarm level: -File nr 175, Day023_Hunting_SSA_ 20211214_104944.mat	**Method of detection**: Data-adaptive ICS filter method. **Figure of reference #1**: ICS indicator trend on front sensor, zoomed for the first 350 measurements. Shows the consistent increasing trend after crossing critical alarm level. Fault Progression Trending Curve - Front
5	Confirmed trend of accelerated fault progression; i.e. a consistent exponential increasing trend started from which file number/name	Critical Alarm level: -File nr 175, Day023_Hunting_SSA_ 20211214_104944.mat Note: difficult to determine where the linear degradation transitions into exponential since the entire indicator curve shows exponential behavior from file nr 175 (R² = 0.965).	**Method of detection**: Data-adaptive ICS filter method. **Figure of reference #1**: Exponential fit of front sensor indicator trend shows entire trend fits exponential curve
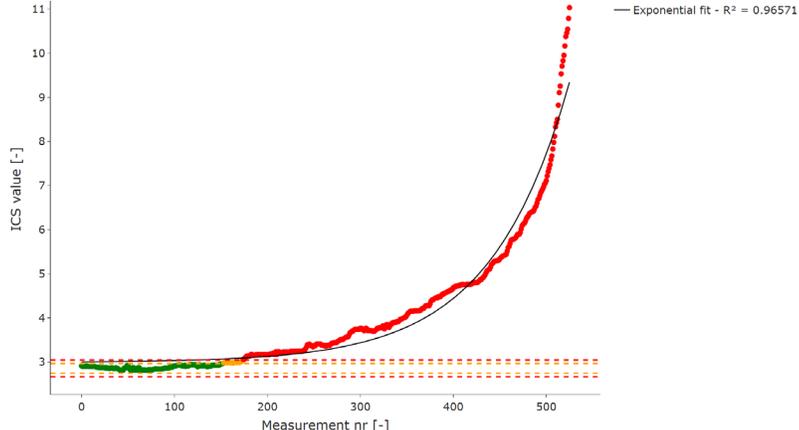
2. Analysis Methods

The used methodology is rather simple since it essentially only uses 1 method, namely a recently developed blind deconvolution method that optimizes a Finite-Impulse-Response (FIR) filter by maximizing the second-order cyclostationarity at specific frequencies (for more details, see references [1] and [2]). In this case, we want to find the impulses related to the planet gear rim crack, which meshes 99 times with both the ring and sun gear in the measured signal, i.e. our cyclic frequencies of interest are thus integer multiples of 2*99. Using a Rayleigh quotient eigenvalue-based optimization, we thus find a FIR filter for each of the 4 channels for all measurements. If there is any vibration source present that has a cyclostationary signature at the chosen frequencies, the iterative eigenvalue estimation will converge at a high Indicator of CycloStationarity (ICS) value and corresponding FIR filter. If there is only noise or the method fails to detect any dominant cyclic source of interest, the ICS value converges at a low value and the filtered signal will not exhibit any improvement. All findings are based on trending these ICS values and on the FIR-filtered vibration signals. For thresholding, Tukey's method is employed as it does not require prior distribution knowledge and has been used many times in the past successfully for thresholding in stationary conditions. The warning threshold is defined as 1.5 times the interquartile range (IQR) from Q1 and Q3, while the critical threshold is 3 times the IQR from Q1 and Q3 (see [3] for more details).

3. Illustrating Figures

See table 1 for the figures.

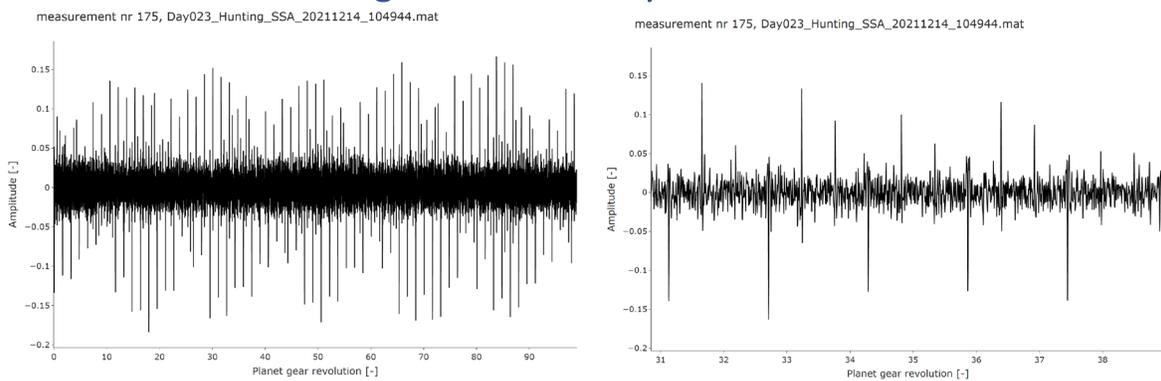## 4. Characteristic Fault Signatures of Early Detection

Figure 1. Characteristic fault signal of the earliest detection by channel RF-2, Front of the gearbox , (Left) full filtered signal with clear impulse structure, (right) zoom of full filtered signal, showcasing the 2 impulses per planet revolution.

[1] Peeters, Cédric, Jérôme Antoni, and Jan Helsen. "Blind filters based on envelope spectrum sparsity indicators for bearing and gear vibration-based condition monitoring." Mechanical Systems and Signal Processing 138 (2020): 106556.

[2] Buzzoni, Marco, Jérôme Antoni, and Gianluca d'Elia. "Blind deconvolution based on cyclostationarity maximization and its application to fault identification." Journal of Sound and Vibration 432 (2018): 569-601.

[3] Malago, M., E. Mucchi, and G. Dalpiaz. "Fault detection in heavy duty wheels by advanced vibration processing techniques and lumped parameter modeling." Mechanical Systems and Signal Processing 70 (2016): 141-160.
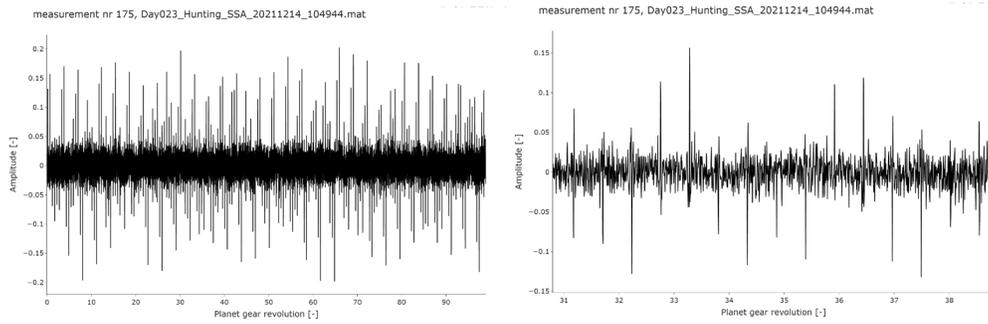
Figure 2. Characteristic fault signal of the earliest detection by channel RR-4, Rear of the gearbox (upper housing flange near ring gear)
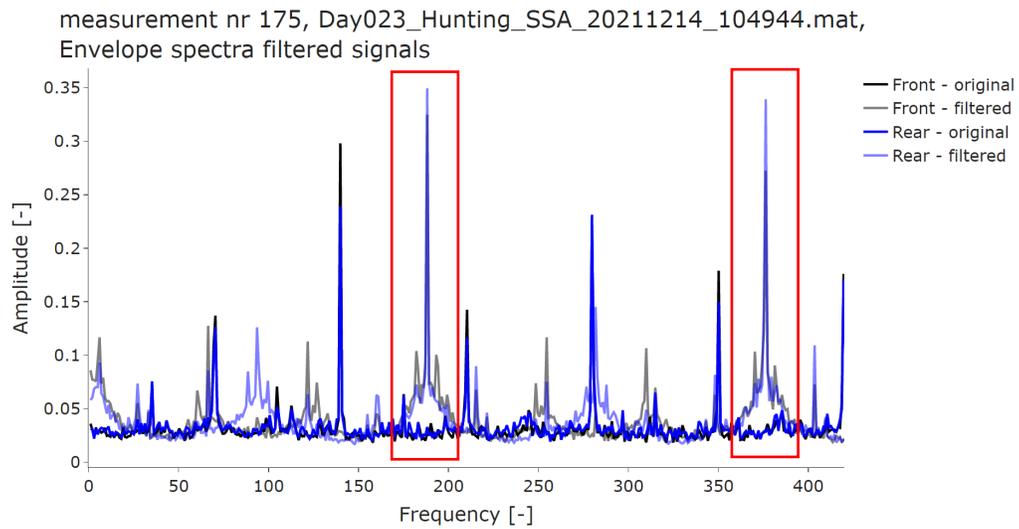

Figure 3. Envelope spectra of the filtered signals. 'Frequency' can be interpreted as number of occurrences in the full signal, i.e. 198 impulses of the rim crack with the sun and ring gear. The original signals are mainly dominated by the planet gear passing modulation, which occurs 4*35=140 times in the full signal.

5. Fault Progression Trending Curve

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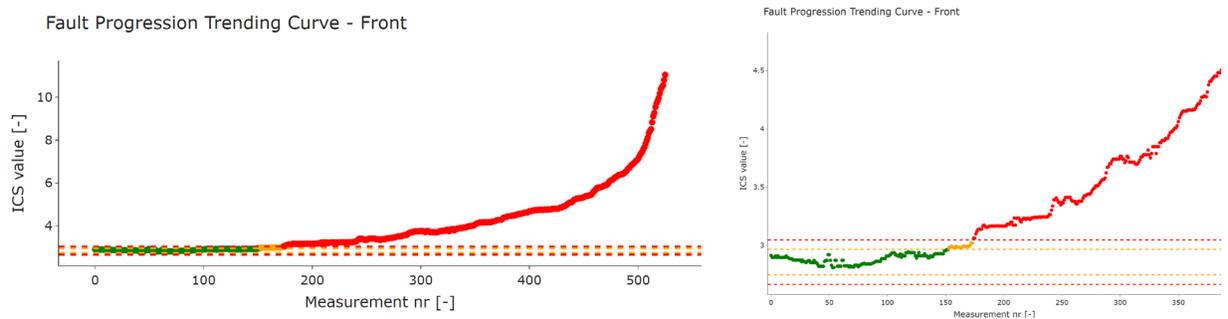

Figure 5. Fault progression trending curve (left) and corresponding zoom for front gearbox sensor. Critical alarm threshold is passed at file nr 175. Entire trend follows a near-exponential curve.
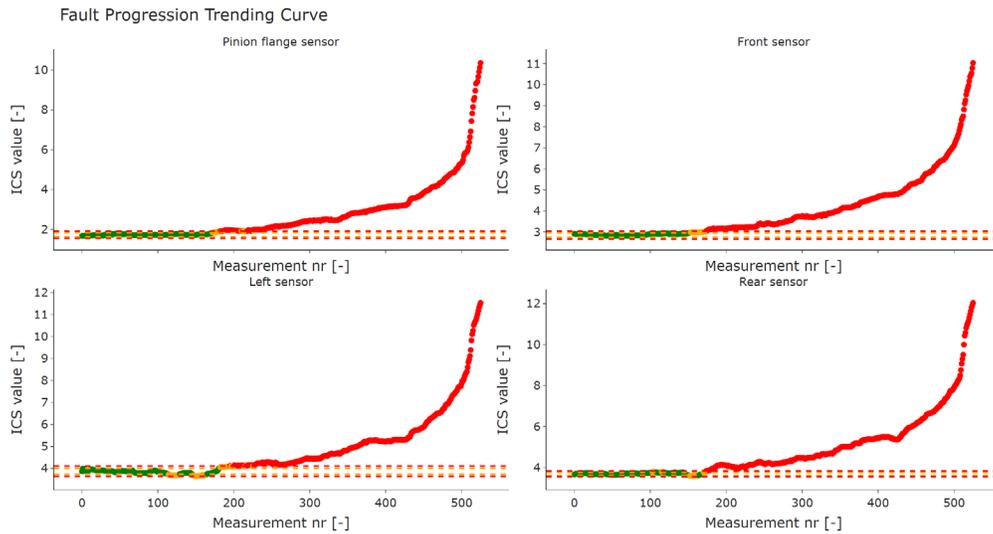
Figure 6. The trending curves for the planet gear fault progression from other channels

6. Description of Analysis Methods

Description of fault detection and trending method

As described in the summary and section 2, fault detection is based on exceeding the critical threshold defined by applying Tukey's method on the ICS values after filtering of the first 100 measurements. These first 100 measurements are considered a healthy baseline. Trending is done with the ICS values. Inspection of fault characteristics is done using the filtered time-domain signals.

7. Supplement Information

As stated briefly in the summary, a noisy characteristic fault impulse train can already be observed in the very first measurement for the radial sensors (see Figure 7). Firstly, this explains the elevated ICS values (≥3) in the very beginning of the radial gearbox sensor fault progression trending curves. Secondly, this seems to corroborate the fact that there was already a rim crack at the very beginning of the shared measurements since we only got the last 60 load cycles. Comparison with a healthy dataset could thus significantly improve the time of detection since the current assumption that the first 100 measurements forms a healthy baseline is probably invalid. Based on the time signals alone, one could argue the time of detection is potentially already file number 1.
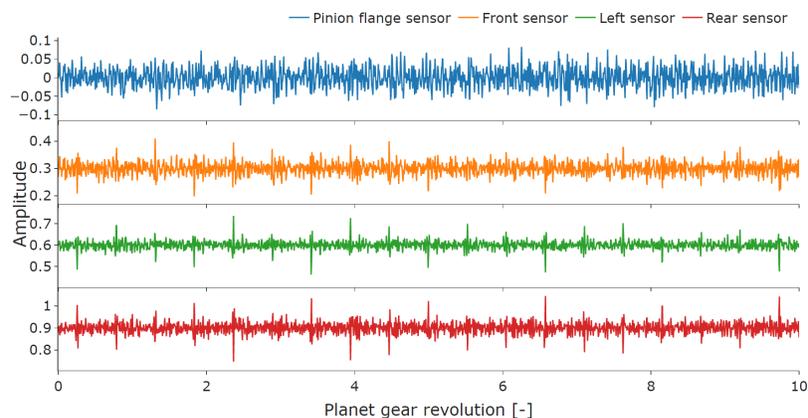

Figure 7. ICS Filtered signals for all 4 sensors for the very first measurement - Day021_Hunting_SSA_20211208_104755.mat