HUMS2023 Data Challenge Result Submission

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Publishable: Yes

1. Summary of Findings

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.	Index 234, file: Day023_Hunting_SSA_20211214_154940 `Sensor: xah{1}`	Based on PFA of 1e-3 Sensor 1, Figure 3
2	Confirmed detection on at least two signal channels; i.e. the fault indicators remain consistently above the threshold.	index 380, file: Day025_Hunting_SSA_20220111_131459 `Sensor: xah{4}`	Based on PFA of 1e-3 Sensor 4, Figure 4
3	Clear multi-channel indication of the characteristic fault features; i.e. faulty planet gear meshing with both the ring and sun gears.	index 254, file: Day024_Hunting_SSA_20211216_104923 `Sensor: xah{1},xah{2},xah{4}`	Based on PFA of 1e-3 from 1, 2 and 4, Figure 6
4	Confirmed trend of fault progression, i.e. a consistent increasing trend started from which file number/name.	index 181, file Day023_Hunting_SSA_20211214_111640	Based on dHI/dt > 0.05, xah{1} Figure 7
5	Confirmed trend of accelerated fault progression; i.e. a consistent exponential increasing trend started from which file number/name	Index 300, file: Day024_Hunting_SSA_20211216_13471	dRUL/dt is 0, RUL is exponential Figure 3, 7, 8

2. Analysis Methods

Two CIs, based on Hunting Tooth analysis (HT) TSA were developed. The period at which these two now damaged teeth mesh is the hunting tooth frequency (*HTF*),

$$HTF = {Gear\ Mesh\ Freq}/_{(\#Teeth\ Pinion\ \times \#Teeth\ Gear)} \quad [1]$$

*CI*1 was based on the sums of the absolute value of the TSA Fourier transform (*fTSA*) for gear tooth order for the planet (35) to (35*99*4), which is the HT order *4. The factor of 4 was chosen as there are four planets.

$$CI1 = \sum_{i=1}^{396} fTSA_{i\times 35} \quad [2]$$

The second analysis, CI2, is similar but normalized by the HTF spectral energy. Nominally, the planet gear mesh should have little modulation (as there are three other planet gears that are synchronous to it), so the ratio should be proportional to the change in gear tooth stiffness.

$$CI2 = \sum_{i=1}^{396} {fTSA_{i\times 35}}/_{HFT} \quad [3]$$

The CIs were then fused and scaled into an HI/ The HI function in the application is the weighted norm of *n* CIs (e.g., the normalized energy of *n* CIs), where the weights are determined by the inverse covariance of the CIs: The HI is:

$$HI = {0.35}/_{critPFA}\sqrt{\boldsymbol{Y}^T\boldsymbol{Y}} \quad [4]$$

where ***Y*** is the whitened, normalized array of CIs, and *critFPA*, is the critical value of the test for some probability of false alarm (set at 1e-3) a value of 6.56. In a hypothesis test, the critical value is calculated from the inverse cumulative distribution function (ICDF) for a given probability of a false alarm. The ICDF is the Nakagami where η is the number of CIs in the array and = *n*, and $\omega = \eta/(2-\pi/2)*2$. If $\boldsymbol{LL}^* = \Sigma^{-1}$, then $\boldsymbol{Y} = \boldsymbol{L} \times \boldsymbol{CI}^T$, where ***L*** is the Cholesky decomposition of the inverse covariance of the CIs from the nominal data. The Nakagami PDF assumes that the distribution of the CIs is Rayleigh. The CIs were "left-shifted" by subtracting the 5% CDF of the CIs, which makes the CIs distribution more "Rayleigh-like."

The HI is scaled from 0 to 1, whereas noted, the detection of a fault occurs at 0.5. The component is in warning at 0.75 and alarm at 1.0. In general, the replacement at an HI of 1.0 gives a safety margin to protect the operator against catastrophic loss.

The filter HI is calculated using an α-β (alpha-beta) smoother, which estimated HI and dHI/dt for each updated acquisition, where the filtered HI is *fHI*:

```
For each HIi update:                                    [5]
  fHIi = fHIi-1 + dHI/dti-1 * dt;   //Updated the Model
  rk = HIi - fHIi;
  fHIi = fHIi + α * rk;
  dHI/dti= dHI/dti-1 + (β*rk)/dt;
```

Where the filter gains were calculated using the process variance is σ_w^2, plant noise variance is σ_v^2, and time from last measurement (*dt*) to give: $\lambda = \frac{\sigma_w dt^2}{\sigma_v}$, and $r = \frac{4+\lambda-\sqrt{8\lambda+\lambda^2}}{4}$, and: $\alpha = 1 - r^2$, and $\beta = 2(2-\alpha) - 4\sqrt{1-\alpha}$. The plant noise variance is, basically, the variance of the HI itself, about 0.04. The process noise variance is related to how fast the degradation process can occur, set at 0.01. This corresponds to a maximum change of 0.1 HI change per hour.

One goal of HUMS is to estimate the remaining useful life (RUL). The component degradation is modeled as a high-cycle fatigue process based on dislocation theory. The crack growth length, *a,* is modeled as:

$$da/_{dN} = \frac{a^2\sigma_{max}^4}{DE\sigma^3} \quad [6]$$

Where *da/dN* is the rate of change of the crack length, *D* is a material constant, σ is the gross stress, and *E* is Young's modulus. The assumption is that the gear HI is proportional to crack length *a*, so by inverting the model integrating and substituting HI for *a,* the RUL can be found is:

$$RUL = {}^{dt}/_{dHI} \times HI_i \times \left(2 - 2\sqrt{HI_i}\right) \qquad [7]$$

3. Illustrating Figures

Figures 1 and 2 show the CI1 trend and CI2 trend for each sensor. Note that sensor 1 appears to have the best signal to noise ratio, and earliest detection. The plots are normalized using the HI algorithm, as this allows a common scale (based on the CI's variance).

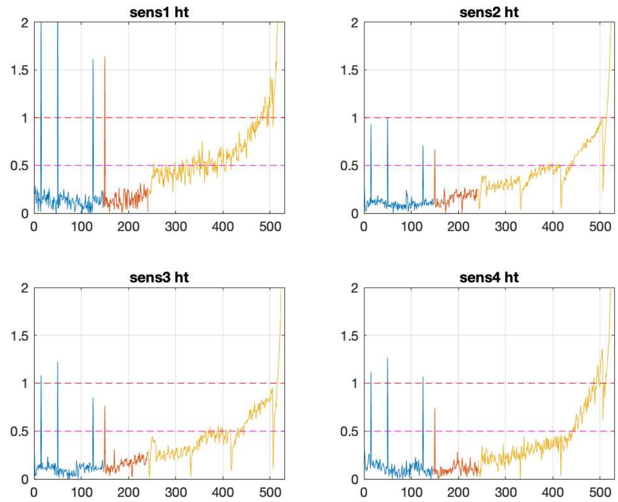


Figure 1 CI1 Trends for Each Sensor.

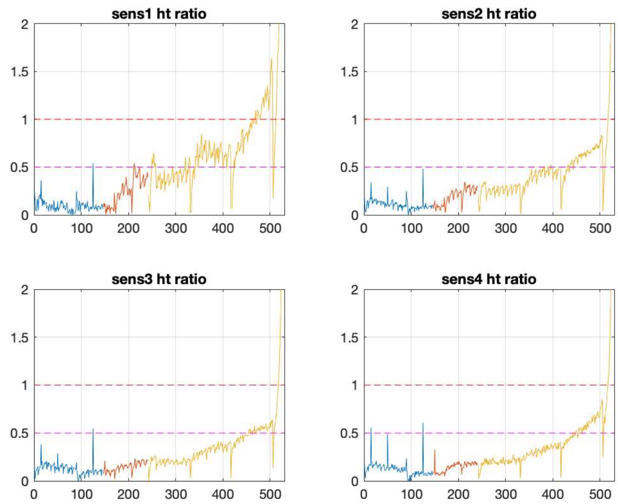


Figure 2 CI2 Trends for Each Sensor

The HI fusion process results in some process gain (about 1.5dB for two independent CIs). Figure 3 uses CIs 1 and 2 and detects the fault at Index 234. The index to recommend maintenance is 379, file Day025_Hunting_SSA_20220111_131200. The HI at the end of the test was: HI > 78.

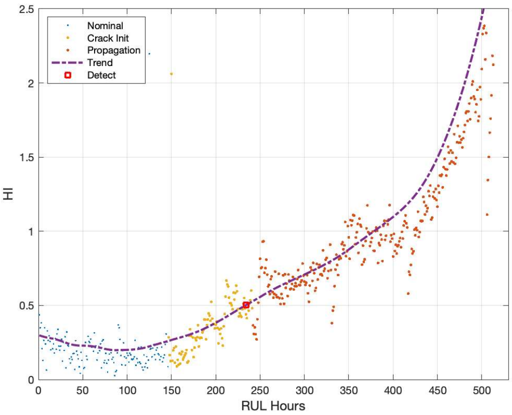


Figure 3 Sensor 1 HI and HI Trend. HI > 0.5 at Index 234

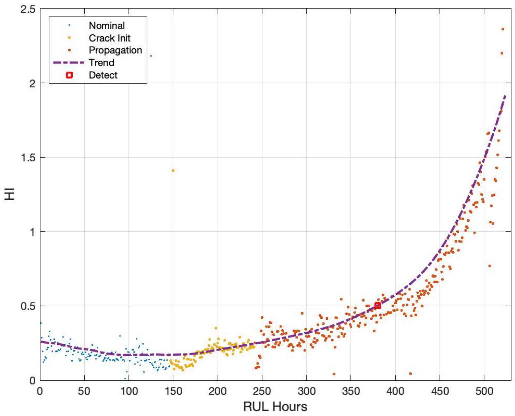


Figure 4 Sensor 4 HI and HI Trend. HI > 0.5 at Index 380

Sensor 4 (Figure 4) detects the fault at Index 380, while recommending maintenance at Index 464. The HI at the end of the experiment as 33. This suggest that the sensor 1 SNR was as least 2x greater than sensor 4. Figure 5 allows a comparison of the HIs from Sensors 1 and 4. Figure 6 shows the HI from using data from Sensors 1, 2 and 4.

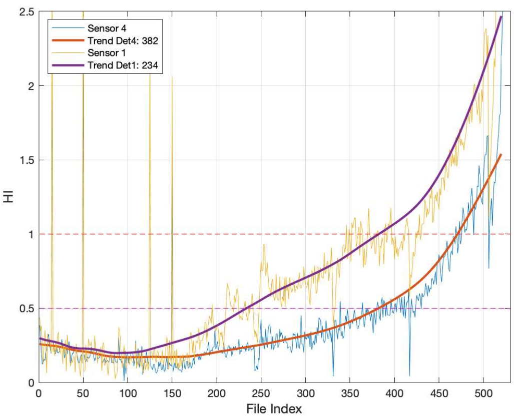


Figure 5 Comparison of Sensor 1 and Sensor 4 HI

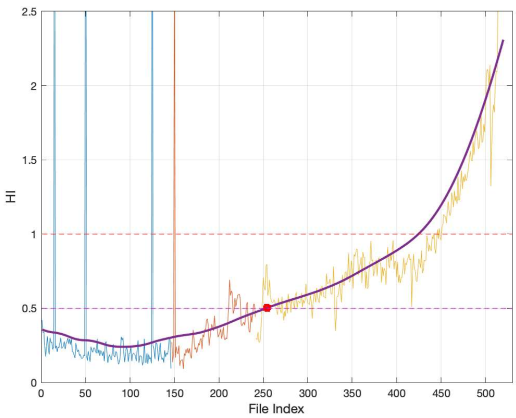


Figure 6 HI Using CIs from Sensors 1, 2 and 4

As the CIs from Sensors 1, 2, and 4 are correlated, there is no process gain in the HI algorithm, so there is no improvement over using just data from Sensor 1.

As the HI trend calculates the derivative of the HI, the fault trend progression is quantifiable. The trend is greater than 0.05 dHI/dt at Index 181 (Figure 7). Figure 8 is the first and second derivatives of the RUL. While the HI growth is nonlinear/exponential, the RUL should be linear. Conceptionally, the point at which the RUL first derivative is -1 (RUL model decrements one hour for each hour of life consumed) and the second derivative is 0 (RUL model is stable) is an indication when the HI growth is exponential. This is taken at Index 300. Note that the Index 300 in Figure 2 and Figure 7 give a similar indication. The RUL model ends at Index 395, and maintenance is recommended at approximately 380.

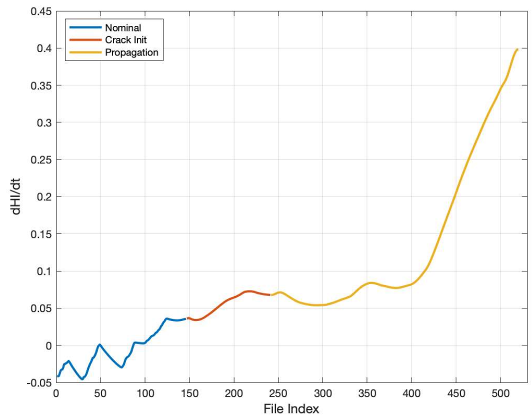


Figure 7 Rate of Change in the HI for Trend Progression

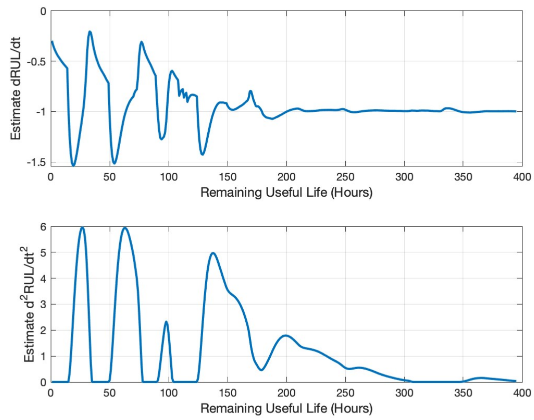


Figure 8 First and Second Derivatives or the RUL

4. Characteristic Fault Signatures of Early Detection

Fault detection is based on some given probability of false alarm. Formally, it is a hypothesis test with the Null hypothesis being that is no fault and the alternative hypothesis being that there is evidence to reject the Null hypothesis (e.g. there is evidence to suggest there is a fault). With a PFA of 1e-3, the Index 234, where the critical value has been set at 0.5. However, in most real-world applications, the Foresight PFA would be set to 1e-6. The fault would then be detected at index 289.

In general, we recommend that maintenance occurs at an HI greater than 1. The maintenance recommendation for the PFA of 1e-3 was index 379. When the PFA was set at 1e-6, that recommendation was index 465. Typically, the performance of a detection process is defined by a receiver operating characteristic. However, these ROC studies difficult as the probability of missed detection is almost never known as it is difficult to define what component damage requires maintenance.

Given that the hypothesis test does not say “the component is bad”, what does fault detection mean? How bad is bad? The small PFA ensures that when maintenance is done there is visible damage. This needs to be balanced with the component having some service life left protect against a potential mishap. In this example, the experiment ended at an HI 78 at Index 526. However, due to the exponential propagation rate, the time to catastrophic failure is accelerated. For example, the HI progressed from approximately 0.2 to 1 in 380 acquisitions but then from 1 to 78 in 147 acquisitions.

5. Fault Progression Trending Curve

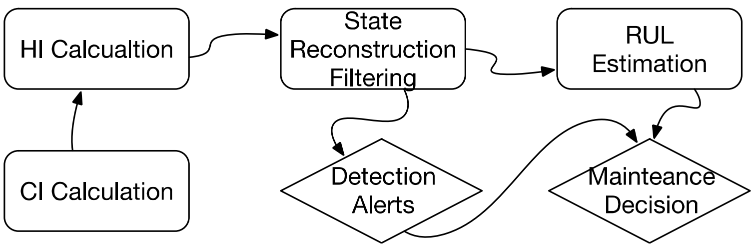
The Foresight system uses an α-β (alpha-beta) smoother for trend analysis This is an extension of the Kalman smoother. The advantage of the α-β smoother is that the filter gains are not calculated dynamically and is computationally fast. A “smoother” is a forward/backward filter: the filter is anti-causal. This guarantees that there is no lag in the filter. The smoother reconstructions the derivative of the trend and better models the dynamics of the degradation process. While degradation is non-linear, the filter assumes piecewise linearity.

Decisions are not made on the raw, unfiltered HI, but only the filtered HI. It is assumed that the measured CIs are stochastic, and that the HI is a function of the CI distributions. Hence, the filtered HI is the best estimator of the true state of the component. The requirement for a fast algorithm, such as the α-β smoother, is that it run whenever new data is available.

The trend of the RUL is also analyzed using a similar α-β smoother. Here the first and second derivatives are used to validate the estimate itself. Physically, it is assumed that the component damage is a fatigue process that can be modeled. There are several modeling assumptions, the first being that the CIs (and resulting HI) are proportional to damage. Fundamentally, if the modeling assumptions are good, the RUL is linear. That is, for each hour of life consumed, the RUL should reduce by one. Hence $dRUL/dt$ should be -1, and if the model is stable, d^2RUL/dt^2 should be close to zero. This information can be used to advise the maintainer on the quality of the RUL estimate.

6. Description of Analysis Methods

Two CIs were developed based on the hunting tooth TSA (eq 2, 3). The CI extracted features related to the energy associated with the 35-tooth planet gear. It is hypothesized that the reduction in tooth stiffness would result in a periodic, non-sinusoidal force which would generate multiple harmonics every 35 orders in the Fourier domain. CI1 summed these energies over four HT periods, while CI2 normalized the sum by the HT spectral energy. The CIs were fused and normalized into a HI. The HI was scaled such that the PFA was 1e-3 at a value of 0.5. The raw HI is then processed by an α-β smoother, which estimates the HI and dHI/dt. As the filtered HI is the best estimate of the HI, detections/alerts are made on this value. The output of the α-β smoother is used to calculate the RUL. The maintenance decisions are then made on the RUL and alert status.



7. Supplement Information

The filtered HI and *dHI/dt* values were used to calculate the RUL using eq 7. The RUL is also used to estimate the fault "trajectory" in Figure 9. The estimated vs actual RUL is in Figure 10.

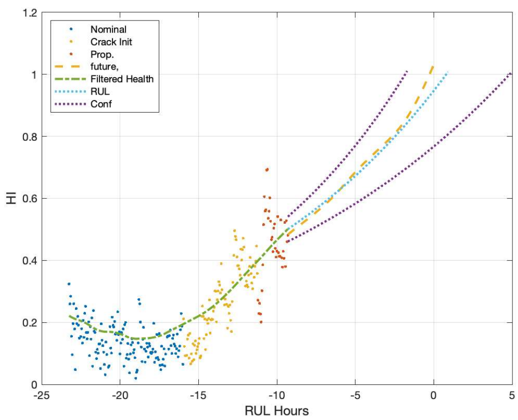


Figure 9 Example Health Trajectory with Confidence

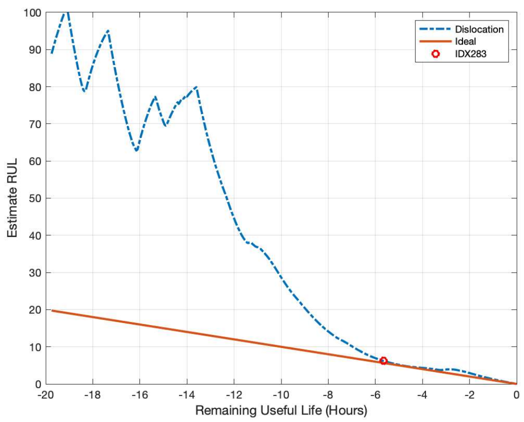


Figure 10 RUL Example