HUMS2025 Data Challenge Result Summary

Team Name: Crack Detectives

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1. Summary of Findings

In this report, a structural health indicator rooted on transmissibility and MAC-Like approach, called frequency-averaged spatial transmissibility coherence (FASTC), is proposed to evaluate the health condition of the gearbox. Then, the Mann-Kendall Test (MKT) is applied to determine whether there is a trend in the indicator. In our work, Hunting-tooth synchronous signal averages (HSSA), bevel synchronous signal averages (BSSA), and pinion synchronous signal averages (PSSA) are used as input to calculate FASTC. Based on the results, FASTC starts decreasing from the first day, which suggests that the casing crack already existed at the start of the experiment. Besides, a statistical test shows a change of behavior in the FASTC, which may be related to the secondary crack, and the file may be "Day012_Hunting_SSA_Pinion_20240501_115742_100%TT.mat".

2. Methodology

In this report, transmissibility, which is obtained from the four frequency responses of vibration sensors, is used to quantify the transfer status of the gearbox system. Then, a metric, called Modal Assurance Criterion (MAC), is applied to evaluate the similarity of transmissibilities respect to different timestamps. Finally, the MKT is applied to detect if FASTC is decreasing. If the FASTC value is close to 1 and does not pass the MKT test, it indicates that the health state of the gearbox remains stable. Conversely, if the FASTC value significantly departs from 1 (in the MKT sense), it suggests that the gearbox health condition is deteriorating. The details of transmissibility, MAC-Like approach and MKT are described in this section.

Transmissibility

Transmissibility is a tool for structural health monitoring (SHM), its equation is:

$$T_{mn}(\omega) = \frac{X_m(\omega)}{X_n(\omega)}, where\ m \neq n, \tag{1}$$

where $m = 1,2,3,4$ and $n = 1,2,3,4$ are the index of sensors, $X_m(\omega)$ and $X_n(\omega)$ are the frequency responses of corresponding sensors and T_{mn} is the transmissibility between sensor m and sensor n. In this study, we assume that the excitations in the gearbox are from the gears, also spatial distributed, can be reduced to a single equivalent coherent force. Hence, when the structural condition of the gearbox changes, the transfer functions, and therefore the transmissibilities also change. The FFT of synchronous average data from four sensors for every file is used to calculate transmissibility. Finally, the form of transmissibility result is $T(t, d, \omega) \in C^{\tau \times D \times L}$, where τ is the time index, $D = 6$ is the number of ratios, and L is the length of subset $\{\omega_l\}_{l=1}^{L}$ of FFT frequencies . Then, the gearbox structure condition can be evaluated with the change of transfer function.

Modal Assurance Criterion

Next, MAC is applied to quantify the similarities in transmissibilities with respect to time and defined as:

$$MAC(t_i, t_j, \omega_l) = \left| \frac{\sum_{d=1}^{D} \left(T(t_i, d, \omega) T(t_j, d, \omega)^* \right)^2}{\sum_{d=1}^{D} (T(t_i, d, \omega)^2) \sum_{d=1}^{D} (T(t_i, d, \omega)^2)} \right|. \tag{2}$$

In equation (2), the dimension of MAC is R^L, and the t_i and t_j are the time index of data files. In other words, the normalized dot product in the dimension of the number of ratios is calculated to detect the similarity between two transmissibility results at different timestamps. Usually, a reference is defined from the early measurements, and we calculate the changes between reference transmissibility and transmissibility obtained from other timestamps. Finally, a series of frequency orders are selected to average the MAC result.

$$MAC(t_i, t_j, \omega_l)^* = \frac{\sum_{l=1}^{L} \left(MAC(t_i, t_j, \omega_l) \right)}{L}. \tag{3}$$

The result of the MAC value of transmissibility is named FASTC. If it demonstrates a trend in time, it is an indication that the structural status changes.

Mann-Kendall Test

MKT is a non-parametric statistical method to detect trends in the time series data. Hence, it's a good tool to detect whether there's a trend in MAC value or not. As defined by Kendall, the sum of differences between observations S are as follows:

$$S(n) = \sum_{i-1}^{k-1} \sum_{j=i+1}^{k} \mathrm{sgn}(x_j - x_i), \tag{4}$$

where sgn(·) is the sign function. The zero hypothesis is that the parameter S is the zero mean Gaussian distribution, and its mean and variance are:

$$E(S) = 0, Var(S) = \frac{n(n-1)(2n+5)}{18}. \tag{5}$$

Then, the standardized Z-score and the p-value is computed as

$$Z = \frac{S - \mathrm{sgn}(S)}{Var(S)}, \tag{6}$$

$$p = 2(1 - \Phi(|Z|)). \tag{7}$$

If the p-value is less than 0.05, the hypothesis is rejected, and the trend exists in the FASTC.

3. Early Fault Detection

Based on the methodology mentioned in the methodology part, FASTC is used to establish the health indicator. Then the Mann-Kendall test is applied to evaluate the health condition of the gearbox. To set the FASTC series value calculated by BSSA signal as an example, the result of the FASTC series and its Mann-Kendall test are shown as follows:

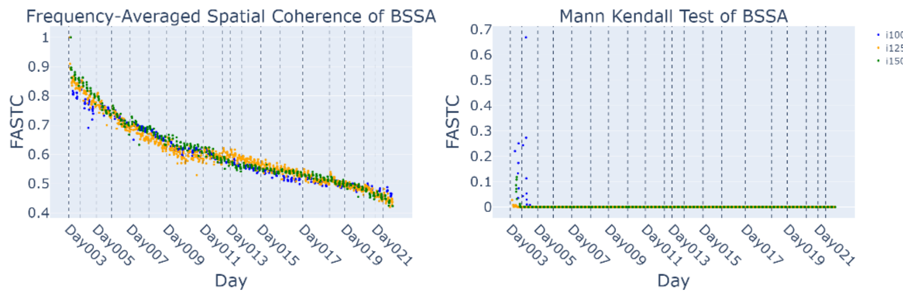


Figure 1 Frequency-Averaged Spatial Coherence of BSSA with selected orders 0-300 and Mann-Kendall test

The selected orders in this case are 0-300, which includes all the gear meshing frequencies (568*Hz* and 1900*Hz*) and most of the relative frequencies, such as sidebands and harmonics. An obvious trend can be found in Figure 1, while the Mann-Kendall test shows that the trend has existed since the second day, Day 4. This indicates that the gearbox casing crack may already exist when the experiment started. Note that FASTC is independent of loading. Three series with different loadings show the same trend, which means that FASTC is not dominated by gear excitation. This also verify our assumption mentioned in transmissibility introduction part that the excitations in the gearbox can be equivalent to a single coherent force.

To further verify the above conclusion, we calculate the FASTC on the gear meshing order and its harmonics, which are 71, 142, 213, and [71,142,213]. Obviously, the performance of the three series on different loading shows differences. On order 71, which is the gear meshing frequency, three series are stable without too much change. For the harmonic orders, the performance of series with 100 loading remains stable, but the performances of series with 125 loading and 150 loading show big different fluctuations. These results, which show no obvious trend, indicate that the manually induced gear spalling fault does not influence FASTC

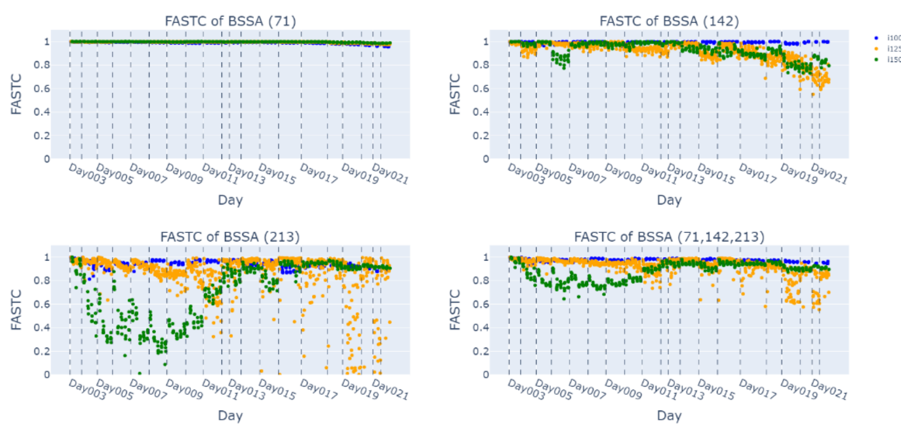
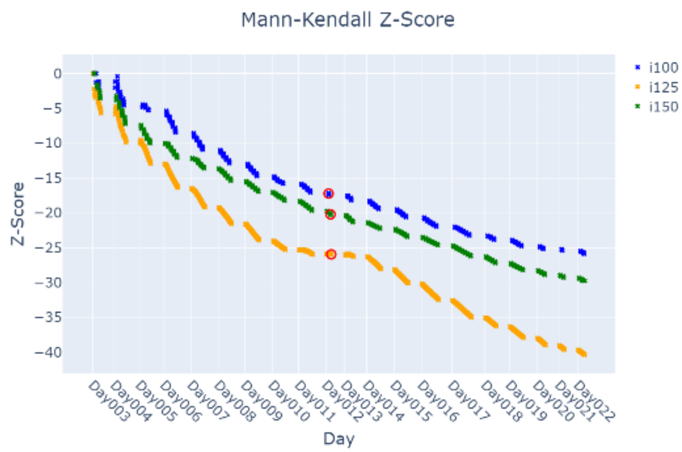


Figure 2 Frequency-Averaged Spatial Coherence of BSSA on order 71, order 142, order 213 and order [71,142,213]

Besides, considering there was a secondary gearbox casing crack during the experiment, our team also tried to detect the timestamp when the secondary crack happened. We can also observe that trends on three loadings have slight change during Day 11 – Day 14 based on Figure 1. Hence, the Pettitt test is applied here to detect FASTC tendency changes. The MKT z-score calculated by equation(6) is used as the input series. The result of the Pettitt test based on the FASTC trend of BSSA is shown as follows:



The red circles are the tendency change points tested by the Pettitt Test, which are all located on Day 12. And the earliest file is "Day012_Hunting_SSA_Pinion_20240501_115742_100%TT.mat". This may suggest that the secondary crack happened on Day012.

4. Fault Progression Trending Curve

Except for the BSSA signal, the PSSA signal and HSSA signal are also analyzed. We calculate the FASTC series of PSSA signal and HSSA signal under the same frequency band order selection mentioned in the above BSSA analysis. The following figures are the results of FASTC trends on different synchronous signal average methods and their Mann-Kendall test results. All kinds of SSA methods show the same trend despite the differences in values. The Mann-Kendall test was all passed on the second day (Day 004). Again, it strongly indicates that the health condition of the gearbox deteriorated when the experiment started.

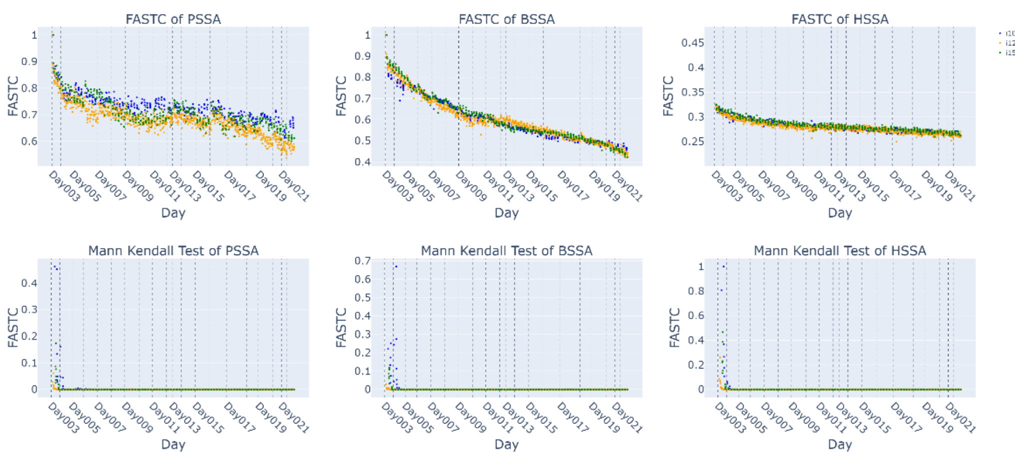


Figure 3 Left: FASTC of pinion synchronous signal averages and its Mann-Kendall test result; Middle: FASTC of bevel synchronous signal averages and its Mann-Kendall test result; Right: FASTC of hunting-tooth synchronous signal averages and its Mann-Kendall test result.

5. Conclusion

To conclude, the health indicator series of FASTC calculated by three kinds of TSA signals all show decreased trends. It indicates that the gearbox casing crack may already exist when the experiment started. In addition, the Pettitt test can detect the tendency change on Day 12. It's a possible indication for the secondary crack., file "Day012_ Hunting_SSA_Pinion_20240501_115742_100%TT.mat".