Strategies to Improve Robustness of a Health Monitoring System, with Application to Brake Rotors

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Abstract

The goal of this paper was to identify strategies that can be employed to improve the robustness of a health monitoring system. Strategies used included:

- Selective signal manipulation which is based on a strategy to apply unique pre-processing and post-processing manipulation techniques to improve the robustness of a health indicator (HI).
- Selective signal blocking which is taking advantage of setting enabling conditions for the algorithm so that signals and the associated noise effects are ignored when the performance of the algorithm is poor.
- Selective signal and HI amplification which is defined as when the system is reconfigured to amplify the signal factor without significantly amplifying the noise effect. An example of such strategy is by applying Time Synchronous Averaging (TSA) to attenuate high-frequency components of a signal with a suspected periodic component.
- Selective HI construction is based on the idea that different sources of signal for development of a prognostics algorithm will lead to different performances and if higher performing HIs in terms of robustness are designed and selected, then the overall performance of the algorithm will be improved.
- Selective signal shaping which is based on the strategy to modify, normalize or change the shape of the input signals to capture some of the relationships between various input signals to the algorithm and improve the robustness and reduce the noise effect.
- Reduce noise effects at the source by applying appropriate filters.
- Generate independent decisions and take an average response and mature the decision.
- Robust parameter design by optimizing the control parameters that impact the performance of the algorithm which can be tweaked and selected by the designer.

This study tested the strategies suggested to a brake rotor health monitoring system and aimed at understanding the influence of vehicle noise factors of tire type, tire pressure and passenger count on a methodology that we developed to detect and isolate early degradation in brake rotors (Kazemi et al. 2019). The fault detection algorithm is designed to detect large rotor thickness variation (RTV), which is the difference between the maximum and minimum thickness of a brake rotor about its circumference. Full factorial experiment was designed, and data collected from vehicle with various healthy and faulty brake rotors.

Robustness of the algorithm to three noise factors of tire type, tire pressure and passenger weight (gross vehicle mass) were investigated. For each noise factor, two levels were considered for comparison. That is, summer tires vs. winter tires, tire pressure at 30 psi vs. 47 psi and passenger count of 1 vs 3 (equivalent to additional weight of 145 kg vs 290 kg to the gross vehicle mass). State of Health estimates across two levels of each noise factor were compared using paired t-test

or signed-rank test and significance levels were considered at p<0.05.

We implemented various strategies to develop a robust health monitoring solution. Selective signal blocking and defining enabling conditions to only use the signals during braking actions that meet specific criteria and ignoring both signals and associated noise effects elsewhere helped significantly improve the robustness. The enabling conditions for the algorithm was defined as when the Vehicle Speed is greater than 10 km/h and Brake Pedal Position (BPP) Feedback is greater than 6 mm and the absolute value of the Brake Pedal Position Gradient (BPPG) is less than 0.005 delta mm and MCP is greater than 1 kPa and longitudinal acceleration (AX) is less than 0 m/s^2 and the ABS Control, stability and traction control statuses are inactive.

Another example of applying selective signal blocking is detecting when the vehicle is traveling on a rough road and ignoring the vibrations caused in the wheel speed during that period.

We also employed selective signal amplification strategy when constructing some of the HIs. The difference of the order analysis of AX signal between the braking period and the normal driving period (non-braking) was employed to reduce the background noise and improve the algorithm robustness. Results showed that the use of this strategy based on measuring the noise during non-brake events and attenuating it by subtracting it from brake events helped robustly predict the thickness variation fault.

In addition, we employed the 'selective signal and HI shaping' strategy. We observed that the ground truth (RTV) and the HIs used to detect RTV (e.g. the envelope of detrended MCP) changes as a function of BPP and therefore there was a need to normalize the HI with respect to BPP. This selective HI shaping and refinement based on another vehicle signal improved the robustness of the algorithm.

Another strategy that we implemented to make the performance of the algorithm less sensitive to the noise factors was through robust parameter design. That is, to optimize the control parameters that can be selected by the designer. In this approach, we systematically explored control factor parameters and searched through the design space while varying noise factors to improve the robustness by optimizing the control and design settings. The choice of pre-processing, filter type and order, maturation window size, enabling condition parameters were some of the factors that were fine tuned to make the system response relatively insensitive to noise factors.

After applying the discussed strategies, the robustness of the overall brake rotor health monitoring algorithm was evaluated. Figure 1 shows the results of executing the paired-samples robustness analysis to the *detrended MCP envelope* HI, one of the highest performing HIs for rotor fault detection. The histograms show the distribution of paired sample differences, which is the difference in average HI value between two tests with all test parameters equal except for the noise factor under test. Note that all three paired-samples error distributions fail the Anderson-Darling (AD) test for normality ($p_n < \alpha$), requiring the signed-rank test to be used to assess robustness. All noise factors have p-values much greater than the significance threshold, leading us to conclude that there is no clear evidence of non-robustness, and that this HI is robust to these three noise factors.

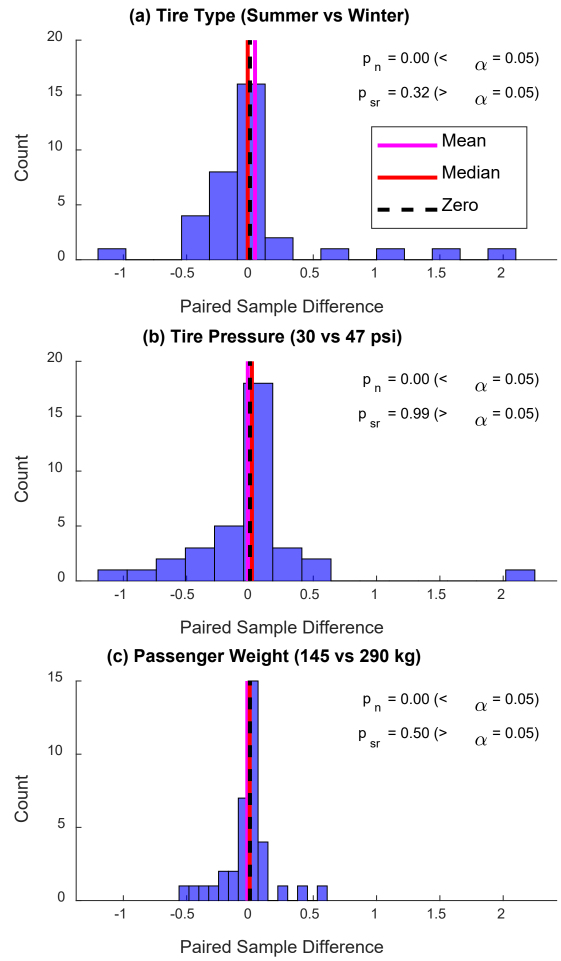

Figure 1: Paired-samples robustness analysis results for the *Detrended MCP Envelope* HI

In essence, results showed that application of the suggested strategies improved the robustness of the algorithm and made the performance of the brake rotor health monitoring system less responsive to the noise factors.

REFERENCES

Kazemi, H., Du, X., Drame, S., Dixon, R., & Sadjadi, H. (2019, September). A prognostics model to predict brake rotor thickness variation. In Annual Conference of the PHM Society (Vol. 11, No. 1).