Condition-based Maintenance of Brake Pads and Tires in Shared Vehicles using Cloud-based Health monitoring and prognostics.

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ABSTRACT

Cloud-based prognostics and health management is a centralized method for monitoring the condition of individual shared vehicles and determining their maintenance schedules. In this study, we focused on monitoring the condition of brake pads and tires, as these crucial components require frequent and regular maintenance for safety. We developed a data acquisition system to transmit data from acoustic and vibration sensors to the cloud server. Useful and efficient features were extracted and selected from time and frequency domains to assess the degradation of brake pads and tires. Moreover, based on feature extraction using the Kruskal-Wallis method, we confirmed that diagnosing brake pad conditions with support vector machines (SVM) provides consistent result for classification of sevierities.. Our preliminary results suggest that cloud-based condition monitoring can be an effective approach to managing shared vehicles.

1. INTRODUCTION

As the market for shared vehicles expands, research on efficient vehicle management and maintenance is being actively carried out.. To address these issues, Condition-Based Maintenance (CBM) technology offers an efficient solution for them by providing efficient maintenance schedule of components that have reached the end of their service life. Implementing CBM can reduce maintenance costs, increase management efficiency, and provide safer vehicles to customers.

Brake pad noise and vibration can lead to uncomfortable driving experiences and impact on the safety. One of the main factors that contributes to these characteristics is wear, as pointed out by M. Triches Jr, et al. To address this issue, most of current research is focusing on developing diagnostic methods for monitoring the condition of brake pad. For instance, Tabbai, Y, et al. investigated the voltage difference of energy harvesting using thermal characteristic changes caused by brake pad wear, while Rajesh, P. K., et al. employed digital twin simulation techniques. Sawczuk, W, et al. (2021) reported that the statistical features of frictional vibration and frequency domain can be used as health indicators of train brake pad wear. Jegadeeshwaran, R., and V. Sugumaran (2015) explained that machine learning techniques have been applied to analyze friction vibration data for monitoring condition diagnosis of brake pad wear and oil leakage in the brake system. Hu, R, et al. (2022) also confirmed that the use of machine learning techniques with a deep subdomain generalization network (DSGN) can effectively identify nonlinear signals of friction vibrations. Xie, M. S., et al. (2014) studies have demonstrated that brake pad condition affects not only the vibration but also the noise generated during brake operation.

In addition, many studies have been conducted to diagnose tire conditions in order to ensure user safety. Methods using laser-based sensors developed by Xiong, Y., and Tuononen, A. (2014), and those using PVDF sensors developed by Yi, J., and Liang, H. (2008), have been utilized to assess the health of tires. Moreover, Joshua, et al. (2016) suggested that sensors built into smartphones can also monitor tire conditions. Furthermore, as Ling, S., et al. (2021) noted, tire wear is a significant factor that affects tire-road noise and vibration. Therefore, condition diagnosis studies using these noise and vibration characteristics were also conducted. Li, T. (2018) presented a study showing that the level of interaction noise between tires and pavement is affected by wear. Additionally, Ho, K. Y, et al. (2013) conducted a study on changes in noise levels according to the condition of the pavement and the period of use of the tire. However, most of these studies were limited to laboratory conditions and did not focus on vehicle applications.

In this study, to address the limitations of previous studies, we propose an experimental setup consisting of a vehicle-mounted Data Acquisition (DAQ) system and a data transmission system via mobile communication services to perform CBM on shared vehicle services. The DAQ system collected data from vibration and PZT acoustic sensors installed in the test vehicle. We identified characteristic features for monitoring the residual thickness of both brake pads and tires. Furthermore, vibration data of various worn pads were obtained as an additional experiment, and the Kruskal-Wallis test was applied to confirm the feature that is mainly affected by the condition of the pad. Finally, it was confirmed that the degree of wear of the pad can be effectively classified using the SVM algorithm using this feature. Based on the proposed approach, the states of brake pads and tires can be monitored and their remaining useful life predicted. Our approach offers the benefits of reduced maintenance costs, increased management efficiency, and enhanced safety for customers.

2. Experimental setup

In response to the potential variability of vibration characteristics due to external factors such as braking conditions, it was decided to preprocess the data using Controller Area Network (CAN) data to filter out unwanted data from certain conditions. To achieve this, data was gathered not only through sensors, but the vehicle's speed and brake operation status were also verified within the CAN data. This method is primarily employed to determine if the data obtained during a single deceleration event is sufficient for analysis and to ensure that the rate of deceleration is neither too slow nor too fast.

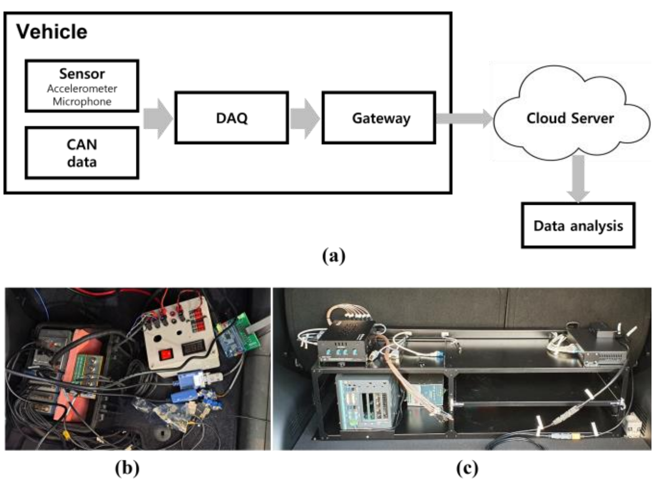


Figure 1. Experimental setup for CBM of Brake pads and Tires(a) Schematic representation (b) Picture of DAQ System (c) Gateway System for transmitting data to a cloud server

The system for monitoring condition and trasfefring data to cloud server was designed to collect, process and to transfer data as described in Figure 1. The process of transmitting information from the sensor to the cloud server is shown in Figure 1 (a), while Figure 1 (b) displays a data acquisition system (NI cRIO 9030, NI 9860, NI 9231) responsible for gathering data. Additionally, Figure 1 (c) represents a gateway system

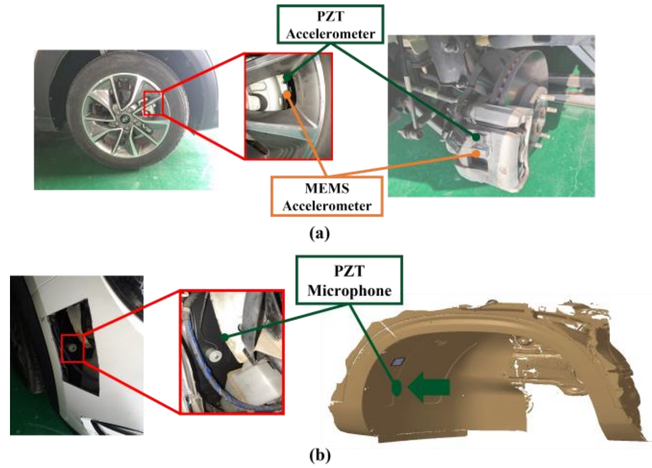


Figure 2. Location of Sensors for data collection (a) PZT and MEMS Accelerometer (b) PZT Microphone

The installed sensors utilized in the experiment are depicted in Figure 2. As demonstrated in Figure 2 (a), four accelerometers on both left and right sides in the front of vehicle were used, including two MEMS-based accelerometers (ADcmXL3021) and two PZT-based accelerometers (PCB 356A15). Also, , as illustrated in Figure 2 (b), the PZT microphone (Cortado MkIII) was mounted on the inner side of the vehicle's fender to minimize exposure to external factors. The data collected from the PZT accelerometer was sampled at 12.8 kHz, while the data from the MEMS accelerometer was sampled at 220 kHz, and the data from the PZT microphone was sampled at 48 kHz.

Figure 3. The tested brake pads and Tires for Health monitoring (a) Tires with a residual thickness of 100%, 60%, and 20% (b) Brake pads with a residual thickness of 20%, 60%, 100%

In this experiment, brake pads and tires with different remaining thickness levels of 100%, 60%, and 20% were tested, as shown in Figure 3. To simulate wear conditions, we control the remaining thickness of the brake pads and tires to the desired levels. We estimated the remaining thickness of the tires using the assumption that the tread depth requiring replacement was 0% thickness. Furthermore, supplementary experiments were carried out to extract features influenced significantly by the condition of brake pads and to verify the applicability of the machine learning classifier. The brake pads with four even-wear brake pads (remaining thicknesses of 100%, 50%, 30%, and 0%, respectively) and four uneven-wear pads (10mm and 20mm wear in the radial direction and 15mm and 30mm wear in the tangential direction) were used.

3. Experimental results

Through the first experiment, the noise and vibration characteristics according to the changes in the residual amount of brake pads and tire treads were identified. In the case of Time Domain characteristics, the data trend according to the change in residual amounts was not confirmed due to the real vehicle driving environment and external noise caused by manual driving. Therefore, the Frequency Domain characteristic analysis was used. In addition, the noise and vibration generated in the brake and tire systems are mainly distributed over a wide range due to friction. Consequently, there is a problem with the Fast Fourier Transform (FFT) and Short Time Fourier Transform (STFT) analysis methods commonly used in rotative system analysis to understand the frequency characteristics of these systems. To overcome this issue, the Frequency domain analysis of the data from the first experiment was carried out using the Power Spectrum Density (PSD) analysis method.

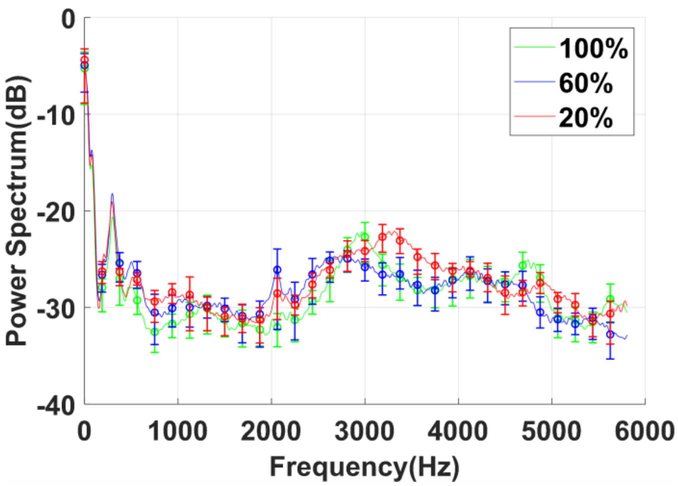
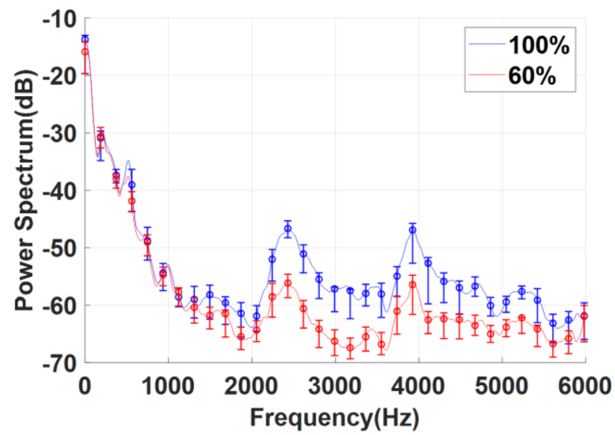
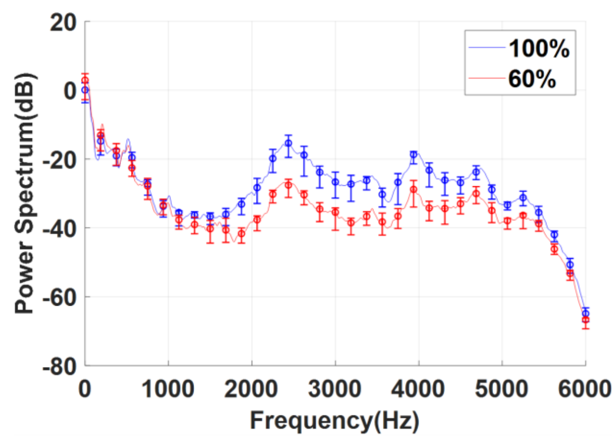


Figure 4. Power spectrum for vibration data of brake pad from MEMS accelerometer as a function of frequency

First, the frequency vibration characteristics of the brake pads using MEMS accelerometer data were verified. In order to analyze the data reflecting the remaining thickness state of the brake pads, signal processing was performed on the data at the time when the brakes were operating in the collected time-series Raw data, and the results are shown in Figure 4. The areas where characteristics are found according to the remaining state of the brake pads are the 3300Hz, 2100Hz, and 4800Hz regions when the remaining pad thickness is 20%, 60%, and 100%, respectively, and it was confirmed that there is a tendency for the magnitude to increase in these frequency ranges for each state..



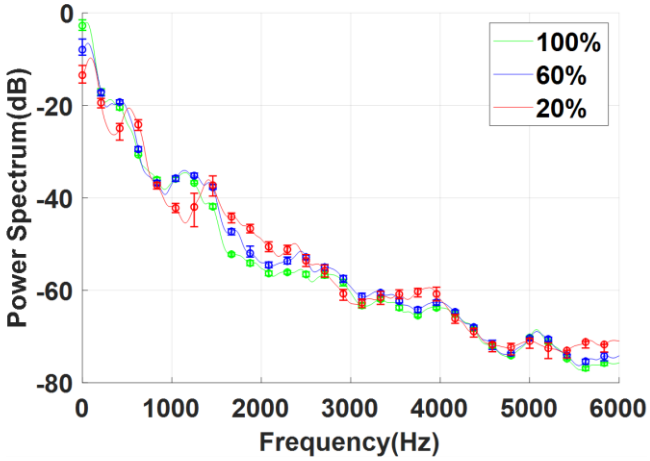
(a)



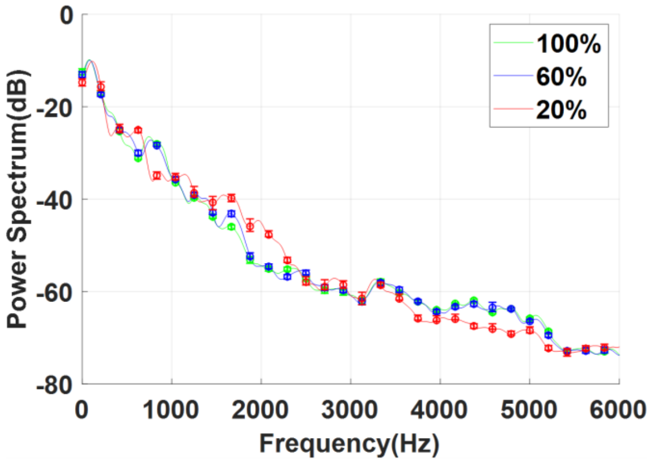
(b)

Figure 5. Power spectrum for vibration data according to tire tread residual thickness (a) MEMS Accelerometer data (b) PZT Accelerometer data

For the diagnosis of tire tread condition, unlike the brake pads, the vibration and noise data were analyzed under conditions where the brakes were not operating and the deceleration was not severe. Figure 5 (a) shows the PSD graph for the MEMS Accelerometer data, and Figure 5 (b) shows the PSD graph for the PZT Accelerometer data. In both MEMS vibration sensor and PZT vibration sensor data, there is a characteristic that the magnitude of the high-frequency range after 1200Hz relatively decreases as the tire wears.



(a)



(b)

Figure 6. Power spectrum for PZT Microphone data based on tire tread residual thickness (a) Vehicle left front wheel data (b) Vehicle right front wheel data.

The PZT Microphone data were measured in the left and right front directions of the vehicle, respectively. No significant difference was observed in the condition of brake pad residual change, while some frequency ranges with tendencies were identified in the condition of tire tread residual change. Figure 6(a) and Figure 6(b) are the PSD results of the left front and right front wheel data of the vehicle, respectively. Commonly, there is a tendency for the amplitude to increase in the 1500~2000Hz range as the tire wears.

Unlike the first experiment, the second experiment was conducted to identify the effective features for classifying the condition of brake pads and to demonstrate the usefulness of the SVM Classification model using these results.

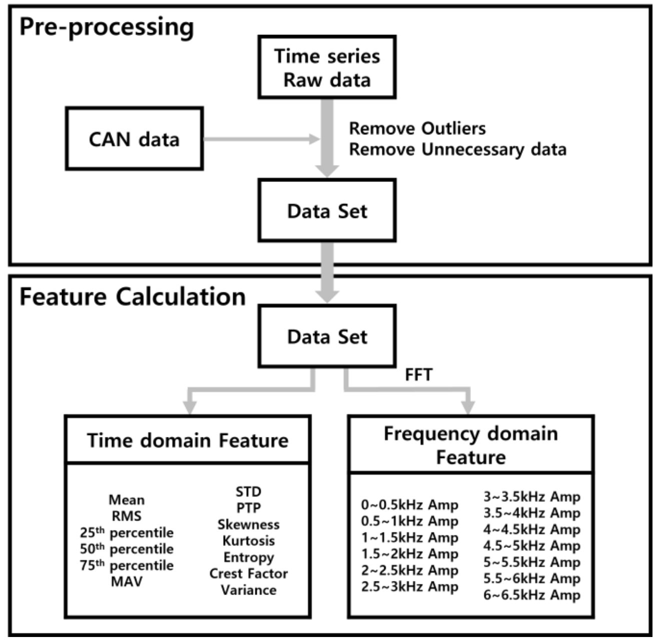


Figure 7. Data Processing Schematic for Feature importance and Machine Learning Classification

Before extracting features from the data, preprocessing of the raw time-series data is performed to remove outliers. One braking attempt, with a vehicle speed of 30~60km/h at the start of braking and decelerating to 3km/h within a time range of 2~15 seconds, is converted into one data set. Ultimately, the central one-second data of each data set is used for Feature Calculation. A total of 26 features are used, including 13 Time domain features and 13 Frequency domain features (the average of frequency amplitude values after FFT calculated every 500 Hz, ranging from 0 to 6500 Hz). The process for calculating these features and the list of detailed features can be found in Figure 7.

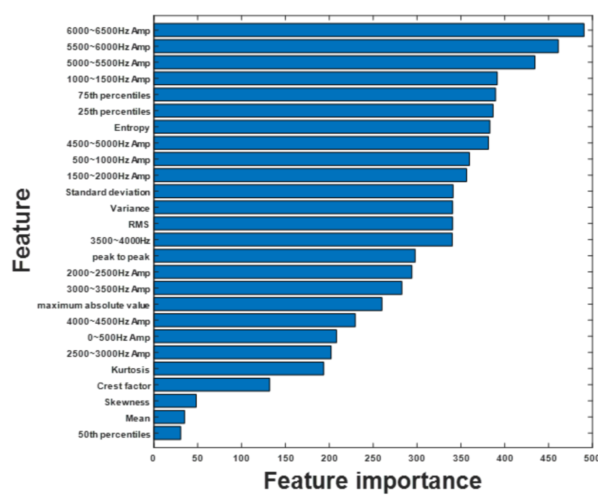


Figure 8. Feature Importance rank of vibration signals using Kruskal-Wallis

The importance of each feature was evaluated using the Kruskal-Wallis Method, and the rankings of importance are specified in Figure 8. Overall, Frequency domain features are considered important features for monitoring the brake pad status, whereas Time domain features have relatively lower rankings of importance. This result can be attributed to the Time domain features not reflecting the brake condition well due to being greatly influenced by noise and external conditions caused by manual driving in real vehicle experiments.

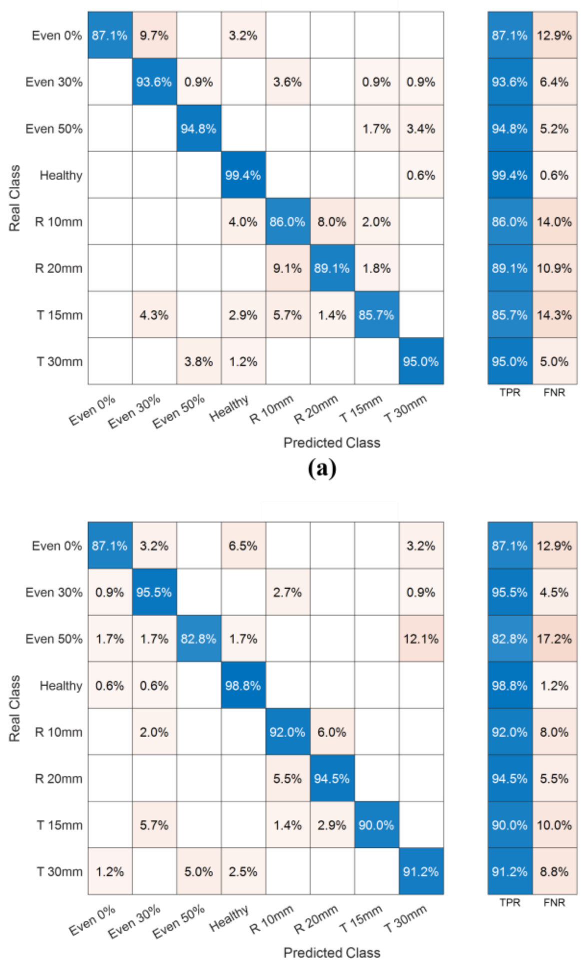


Figure 9. Confusion matrix of SVM Classifier using PZT Accelerometer vibration data feature (a) using 26 Feature (93.0%) (b) using 10 feature (93.0%)

Feature After the feature selection process, brake pad condition diagnosis was performed using the SVM machine learning classifier. Although various classifier algorithms exist for machine learning classifiers, such as the Decision Tree and KNN (K-Nearest Neighbor) Method, the SVM algorithm, which is commonly used for classification, was employed in this study. Validation was carried out using a 5-group Cross-Validation Method, with a total of 626 data sets utilized for training and validation. Models using all 26 features and the top 10 features based on Feature Importance results are presented, with the validation confusion matrices for each model shown in Figure 9 (a) and Figure 9 (b). The brake pad wear conditions are denoted as follows: even wear is "Even," radial direction uneven wear is "R," and tangential direction uneven wear is "T." Both models demonstrate an accuracy of 93.0% for classifying the eight conditions, indicating that using the Kruskal-Wallis Method to reduce the number of features is effective..

4. Conclusion

In this paper, a method for diagnosing the condition of brake pads and tires using acoustic and vibration sensor data, and an overall cloud-based condition monitoring system, were proposed. For cloud-based monitoring, an integrated system based on a data acquisition device that collects data from various sensors including CAN and GPS data was established. The collected data is transmitted to a cloud server through a gateway, and the implementation method of cloud-based condition monitoring was presented.

Frequency characteristic analysis studies for the diagnosis of the remaining state of brake pads and tires were also conducted. In the case of brake pads, it was confirmed that data with a tendency in a specific frequency range was secured depending on the remaining state. In the case of tire treads, it was confirmed that the amplitude in the high-frequency range of vibration data decreases due to the change in tread thickness, and a tendency depending on the change in tread thickness was found in the acoustic sensor data in the 1800-2000Hz range.

In addition, a Feature Importance analysis using the Kruskal-Wallis method was conducted to find characteristics that reflect the state of brake pads. As a result of the analysis, it was found that the frequency domain features were more affected by the condition of the brake pad than the time domain features. Subsequently, the accuracy of brake pad condition diagnosis using an SVM classifier was confirmed to be more than 93%. Moreover, by using Feature Importance analysis to reduce the number of features, it was possible to propose a method that could reduce the learning and processing time and cost of SVM classifier modeling while maintaining the same classification accuracy.

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