International Journal of GEOMATE, March, 2020, Vol.18, Issue 67, pp. 195-201
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2020.67.5554
Special Issue on Science, Engineering and Environment

CORRELATION ANALYSIS OF VIBRATION AND SOUND SIGNALS OF A GASOLINE-ENGINE CAR

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*Corresponding Author, Received: 17 April 2019, Revised: 20 Nov. 2019, Accepted: 11 Jan. 2020

ABSTRACT: Nowadays, the number of petroleum-fuel vehicles has been continuously increasing despite of the arising of electric vehicles. Thanks to the environmental concerns, the EV is being developed in both of its performance and cost reduction aspects. However the petroleum-fuel vehicles are still popular because of their more economical sale prize, low-cost maintenance, and wider after-sale services. This paper presents the correlation between the vibration and sound signals of a personal gasoline engine car, since the important interfaces of the car users are the perceived vibration and sound signals. In the experimental design, three vibration sensors and three condensed microphones at different positions have been allocated systematically according to the most perception of car users. A quantity of the engine vibration and sound signals have been measured and prepared as collections of signal databases. The signal feature of first pitch is considered due to its indication of main engine frequency. The fast Fourier transform (FFT) is applied the frequency spectrum of the signal in all databases. Subsequently, the first dominant peak occurring in the spectrum is selected and recorded for both of its frequency and its magnitude. These attributes are then analyzed as comparison with different engine speeds. Finally, the correlations of these attributes between the vibration and sound signals are presented. From the proposed correlation function, some pairs of the signal features expose significant relationships, for example, the sound signal at the exhaust pipe and the vibration signal at the seat when considering the magnitudes at the emerging dominant frequencies.

Keywords: Correlation analysis, Fast Fourier transform, Gasoline-engine car, Vibration signal, Sound signal

1. INTRODUCTION

Presently, a quantity of alternative sources of energy are being developed to utilize in the industry, business, and transportation sectors. The energy such as gasohol, biodiesel, Hydrogen, and electricity are very popular in the near future. However, the production cost of these alternative sources of energy is still expensive comparing with the petroleum resources. Therefore, the gasoline and diesel oil production is still being developed in both the quality and the efficiency in term of its formula.

By investigating a number of reviews on the detection and diagnosis of the faults in rotating machinery, it has been reported that the mechanical vibration-based studies have been widely conducted [1]-[3]. The related studies are seldom applied with the gasoline or diesel engines. The utilizations of vibration-based techniques to these engines are considerably burdensome due to the transient and non-stationary nature [1]. The application of vibration signals of engines brings about the dynamic movement of the mechanical system condition. A number of powerful signal processing techniques have been studied for fault diagnosis [2]. The power spectrum with high order, cepstrum, and neural network were investigated in the specified-type induction motor fault diagnosis and indication [4]. The discrete wavelet transform was exploited efficiently with the vibration signal of the diesel engine and the gearbox for the engine fault diagnosis [2]-[3]. The power of signal analysis was adaptively conducted due to its less time consumption and low complexity [5]-[6]. Since the different temperatures of the engine combustion make the working condition of the engine changed, the problems of LPG-installation cause the variation in engine vibration and sound [7]-[10]. As a result, the vibration and sound signals are investigated to distinguish between the LPG-installation engine and the normal gasoline engine, because they are ones of important measurable attributes to indicate the causes of irregular conditions of engines [11]-[12]. A study of vibration and sound signal analysis for a gasoline engine with LPG-installation and fault simulations was performed recently [13]-[15]. The findings summarized that LPG-installation and engine faults cause degradations in engine efficiency which can be concretely evidenced by using the proposed signal processing technique of the absolute averaged power of signal and the averaged peak of signal.

In this study, the correlation of vibration and sound signal attributes has been introduced. It is expected from the proposed approach that some

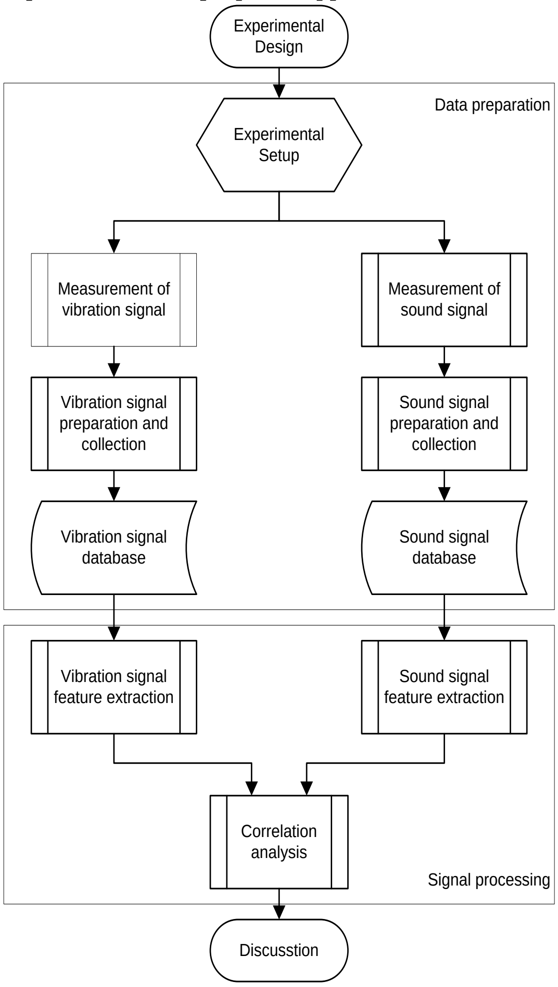

Fig. 1 Experimental Procedure

significant relations are found and summarized.

In the experimental design, the procedure is divided into two stages including data preparation and signal processing. At the first stage of the experiment, the experimental setup has been performed firstly. Subsequently the signal measurement for all designed cases has been done. Finally the signal preparation and collection has been conducted to construct the signal database. The vibration and sound signal databases have been implemented in parallel in this stage. In the second stage of this experiment, the signal processing has been applied. At the beginning, the signal feature extraction has been performed. The frequency spectrum of this prepared corresponding signal has been conducted by using fast Fourier transform technique. A number of frequencies at the dominant peak points in the frequency spectrum and their corresponding amplitudes have been extracted. The highest peak is assumed to represent the fundamental frequency generated from the moving machine. These features are therefore analyzed and subsequently used in the correlation analysis. It has

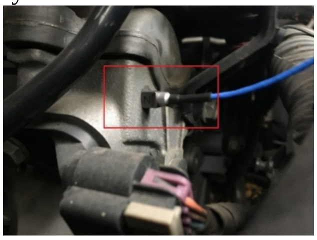

Fig. 2 A position of the vibration sensor : the surface of the engine pistons

Fig. 3 Two positions of the vibration sensors : the backrest and the bottom seat of the cushion beside the driver

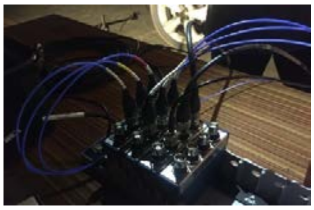

Fig. 4 Connection of all sensors with the NI cards, NI rack

Fig. 5 A position of the microphone : a position at the neck of the backrest of the cushion beside the driver

Fig. 6 A position of the microphone : a position beside the front wheel with 0.5-meter far distance

Fig. 7 A position of the microphone : a position at the rear of the exhaust pipe with a 45-degree angle to that pipe and a 0.5-meter far distance

been stated that the correlation analysis is used to measure the level of correlations between corresponding vibration and sound signals by setting a couple of function criterions. At the end of the stage, the discussion of the study has been performed.

2. MATERIAL AND METHODS

The material and the methods are elaborated by using the experimental procedure as illustrated in Fig. 1. The review of the procedure is presented in the following subsections.

2.1 Experimental Design

At the beginning of the procedure, the experimental design process has been inaugurated. All experimental equipment includes a personal car with gasoline engine (Chevrolet Captiva brand with 2.4 liter engine, Double CVC, 4 cylinders, and 16 valves), vibration sensors and their accessories, condensed microphones and their complementary parts, NI card for interfacing with computer, and a computer for signal processing. In parallel, these vibration and sound signal retrieving setups are designed to allocate at the personal car.

2.2 Data Preparation

As for the data preparation stage, the experimental setup is conducted to retrieve the vibration and sound signal from the specimen car in a number of engine speeds at the parking stage in parallel. Three steps of the measurement, preparation and collection, and database implementation are performed in this data preparation stage, respectively.

2.2.1 Experimental Setup

In the experimental setup, the vibration and sound signal retrieving setups have been prepared. Three sets of high-frequency vibration sensors and three condensed microphones are allocated at different positions inside and outside of the car. The corresponding signals are then transferred into the processing computer through a group of NI interfacing cards in parallel.

2.2.2 Vibration Signal Retrieving Setup

In the experimental setup, three sets of high-frequency vibration sensors are located at three different positions including the surface of the engine pistons as depicted in Fig. 2, the backrest and the bottom seat of the cushion beside the driver as depicted in Fig. 3. All vibration signal wire are connected with the NI cards which are attached with the NI rack as depicted in Fig. 4. The rack is also connected to the computer which all signals are retrieving into the Labview program in parallel.

2.2.3 Sound Signal Retrieving Setup

In the experimental setup, the sound signal retrieving setup is almost the same as that of vibration signal retrieving setup. Three positions installing the microphones are including a position at the neck of the backrest of the cushion beside the driver as shown in Fig. 5, a position beside the front wheel with 0.5-meter far distance as shown in Fig. 6, a position at the rear of the exhaust pipe with a 45-degree angle to that pipe and a 0.5-meter far distance as shown in Fig. 7. The NI cards and the NI rack are also used for retrieving sound signal.

2.2.4 Measurement of Vibration Signal

In the measurement of vibration signal, a number of vibration signals of the tested car are measured at three different points as depicted in Figs. 2 and 3. The sampling frequency is at 50,000 Hz. Ten samples with 5 seconds of the vibration signal are measured for 6 different engine speeds of idle, 1500, 2000, 2500, 3000, and 3500 rpm, respectively.

2.2.5 Vibration Signal Preparation and Collection

After the signal samples are retrieved through Labview program, the preliminary process of signal segmentation are subsequently conducted. The collection of signals from all distinguished sensor positions and all different engine speeds are categorized into six groups.

2.2.6 Vibration Signal Database

At the end of data preparation stage, the database of the categorized signals is implemented. Three subsets of categorization are including the signals from the surface of the engine pistons, the signals from the backrest of the cushion, and the signals from cushion seat. In each subset, the signal portions are dividing into six groups corresponding to each engine speeds as described previously.

2.2.7 Measurement of Sound Signal

In the measurement of sound signal, a number of sound signals of the specimen car are measured at three different points as depicted in Figs. 5-7. The sampling frequency of the sound is also set at 50,000 Hz. Ten samples with 5 seconds of the sound signal are measured for 6 different engine speeds as same as those of vibration signal.

2.2.8 Sound Signal Preparation and Collection

After the sound signal samples are retrieved through Labview program, the preliminary process of signal segmentation are subsequently implemented. The collection of sound signal from all three sensor positions and all different engine speeds are also categorized into six groups.

2.2.9 Sound Signal Database

Before entering into the signal processing stage, the database of the categorized sound signals is implemented. Three subsets of categorization are including the signals from the position at the neck of the backrest of the cushion, the position beside the front wheel, and the position at the rear of the exhaust pipe. In each subset, the signal portions are also dividing into six groups corresponding to each engine speeds as described earlier.

2.3 Signal Processing

In the signal processing stage, the feature extraction and correlation analysis are performed respectively. The explanation is presented in the following subsections.

2.3.1 Vibration Signal Feature Extraction

The signal processing technique of Fast Fourier transform (FFT) has been applied with all of the portions of the vibration signals for all groups within the database. From the output frequency spectrum, the most dominant peak appearing the frequency domain is extracted. Subsequently, the frequency and magnitude at the peak are investigated and also utilized in the correlation analysis.

2.3.2 Sound Signal Feature Extraction

The similar signal processing technique of FFT is also applied with the sound signal database. The extracted features from both vibration and sound signal are then used as input of the correlation analysis in the next step.

2.3.3 Correlation analysis

In the correlation analysis, a couple of product functions in the same sense as the cross correlation function have been adopted. A summation of the multiplication of between two set of signal features at all engine speeds is calculated and used as these product functions. The higher the function value, the more the mutual relation is. The first function is defined as follow,

$$\boldsymbol{cf(sf_i, vf_j)} = \sum_{N=1500}^{N=3500}(\boldsymbol{sf_i . vf_j}), \quad (1)$$

where sf_i is the peak frequency dominated in the sound spectrum at the ith position, vf_j is the peak frequency dominated in the vibration spectrum at the jth position, N denotes the engine speed ranging from 1500 to 3500 rpm. Moreover, another function is defined as follow,

$$\boldsymbol{cm(sm_i, vm_j)} = \sum_{N=1500}^{N=3500}(\boldsymbol{sm_i . vm_j}), \quad (2)$$

where sm_i is the magnitude at the peak frequency dominated in the sound spectrum at the ith position, vm_j is the magnitude at the peak frequency dominated in the vibration spectrum at the jth position, and N is defined as same as that of the first function.

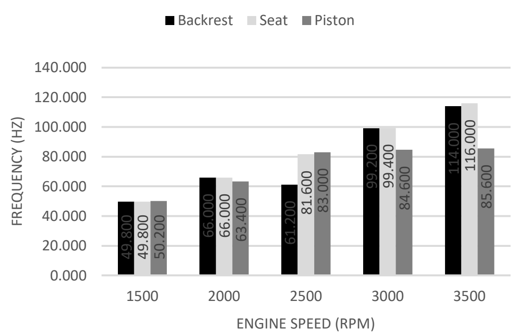

Fig. 8 The emerging dominant frequencies of the vibration signal at five different engine speeds

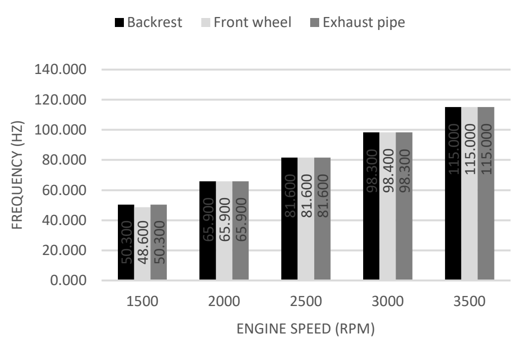

Fig. 9 The emerging dominant frequencies of the sound signal at five different engine speeds

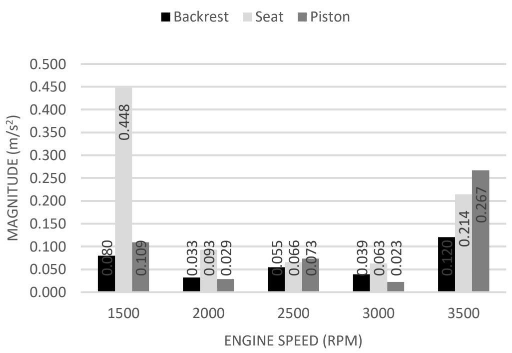

Fig. 10 The magnitudes of the FFT at the emerging dominant frequencies of the vibration signals at five different engine speeds

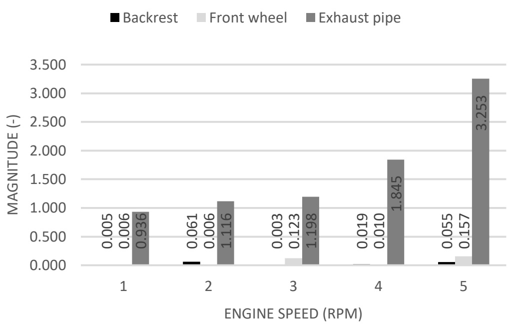

Fig. 11 The magnitudes of the FFT at the emerging dominant frequencies of the sound signals at five different engine speeds

Table 1 The correlation evaluation by using the emerging dominant frequencies

$cf(sf_i,vf_j)$	sf_1	sf_2	sf_3
vf_1	34709.620	34634.880	34709.620
vf_2	36623.920	36549.200	36623.920
vf_3	31636.100	31559.220	31636.100

Table 2 The correlation evaluation by using the magnitudes of the FFT at the emerging dominant frequencies

$cm(sm_i,vm_j)$	sm_1	sm_2	sm_3
vm_1	0.010	0.027	0.641
vm_2	0.021	0.046	1.416
vm_3	0.018	0.052	1.133

2.3.4 Discussion

The interpretation of the output correlation is performed by using the calculated values of those couple functions. Finally the discussion for all aspects has been completed and presented in the experimental results.

3. EXPERIMENTAL RESULTS

In this section, the experimental results consist of three parts including the result of emerging dominant frequency, the result of magnitude of the FFT at the emerging dominant frequency, the result of cross correlation analysis, respectively.

3.1 Emerging Dominant Frequency

In the vibration and sound signal analysis, the efficient signal processing technique of FFT has been applied to determine the frequency spectrum of both prepared vibration and sound signal databases. These output spectrums are in frequency domain of Hertz unit. The emerging dominant frequencies at the peak point at five different engine speeds are extracted and plotted in the following bar charts in Figs. 8 and 9. Graphically, Fig. 8 presents the averaged values of emerged frequencies at five different engine speeds for the vibration signal, meanwhile Fig. 9 presents those of the sound signal.

From Figs. 8 and 9, it can be obvious seen that the emerging dominant frequencies of the vibration and sound signals are approximately directly proportional to the engine speeds. These emerging frequencies reflect the fundamental frequencies of the engine which correspond to the relation $f = \frac{iN}{2\times 60}$, where i denotes the number of engine pistons which is 4 for this study, meanwhile N presents the engine speed in rpm.

3.2 Magnitude of the FFT at the Emerging Dominant Frequency

Beside the emerging frequencies, the corresponding magnitudes at the peak points of the frequency spectrum of vibration signal are extracted for all five different engine speeds. Subsequently the corresponding averaged values are plotted as a bar chart and depicted in Fig. 10. Moreover, Fig. 11 shows the magnitudes for the sound signal.

From Fig. 10, it can be noticed that the magnitudes of the FFT at the emerging dominant frequencies of the vibration signals are relatively high at the engine speeds of 1500 and 3500 comparing with the other speeds. Moreover these magnitudes are roughly increased when the engine speed is raised. In Fig. 11 where the magnitudes of the FFT at the emerging dominant frequencies of the sound signals are focused, it can be explicitly observed that those of the exhaust pipe are highest, meanwhile those of the backrest are lowest. Last but not least, the magnitudes tend to increase, when the engine speed is raised up.

3.3 Cross Correlation Analysis

A couple of cross correlation functions are applied to measure the correlation between vibration and sound signals of the tested car. Firstly, the correlation evaluation by using the emerging dominant frequencies is conducted and depicted in Table 1. Subsequently, the correlation evaluation by using the magnitudes of the FFT at the emerging dominant frequencies is conducted and presented in Table 2.

From Table 1, it can be observed that the correlation of the emerging dominant frequencies of the vibration signals with the emerging dominant frequencies of the sound signals is relatively highest at the position 2 or at the seat, meanwhile it is lowest at the position 3 or at the piston. From Table 2, it can be noticed that the magnitudes of the FFT at the emerging dominant frequencies of the sound signals with the magnitudes of the FFT at the emerging dominant frequencies of the vibration signals is relatively highest at the position 3 or at the exhaust pipe, meanwhile it is lowest at the position 1 or at the backrest. Moreover, the sound signal at position 3 or the exhaust pipe and the vibration signal at position 2 or the seat disclose the maximum correlation function value, when considering all pairs of the concerned signals.

4. CONCLUSIONS

A study of the correlation analysis between the vibration and sound signals of a personal gasoline engine car is presented in this paper. Three vibration sensors and three microphones are located at different positions according to the most perception of car users. The correlations of these attributes between the vibration and sound signal are finally presented. FFT has been used with the vibration and sound signals. From the output frequency spectrum, the most dominant peak appearing the frequency domain is extracted. The frequency and magnitude at the peak point are analyzed and used in the correlation analysis. From the proposed correlation function, some pairs of the signal features reveal significant relationships, for example, the sound signal at the exhaust pipe and the vibration signal at the seat when considering the magnitudes of the FFT at the emerging dominant frequencies. In the future research, the other derivatives of the correlation functions should be developed to obtain more efficient indications of relationship between the considered signals. Last but not least, the application of this study to the engine-fault diagnosis is expected to be studied.

5. ACKNOWLEDGMENTS

The research study is partly supported by Faculty of Engineering at Sriracha’s Funds of Kasetsart University. Morever, the experimental instruments and workforces are provided by the research group of Mechanical Systems and Signal Processing, (MESSI) of Faculty of Engineering at Sriracha.

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