International Journal of GEOMATE, April 2023, Vol. 24, Issue 104, pp.77-84
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2023.104.s8532
Geotechnique, Construction Materials and Environment

INVESTIGATION ON VIBRATION AND SOUND SIGNALS FROM HYBRID-ENGINE TO ELECTRIC VEHICLES

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*Corresponding Author, Received: 14 Mar. 2022, Revised: 12 Jan. 2023, Accepted: 26 Feb. 2023

ABSTRACT: Electric vehicles have been increasingly popular compared to conventional combustion engine vehicles. Along the way, hybrid electric vehicles have been developed to truly bridge the transition from internal combustion engines to electric vehicles. Therefore, an analysis of vibration and sound signals of a HEV and an EV is necessary to evaluate the quality of service comparatively. As for the HEV test with three measuring scenarios, the experimental data are collected and subsequently, the dominant frequency extraction is conducted. The hybrid-drive mode shows the highest level of vibration magnitude for all tested speeds; however, some scenarios of engine-drive mode are higher than hybrid-drive mode due to the engine and battery setups. Last but not least, the sound signal analysis is performed with the same scenarios. It has been seen that the levels of both sound and vibration magnitudes directly vary with the engine speed. As for the EV test, when the electric car starts to work by increasing the speed, its vibration and sound magnitudes measured at three distinct positions increase accordingly. This study is the basis for further development of the next generation EV in the vibration and sound passenger perception aspects.

Keywords: Hybrid electric vehicle, Electric vehicle, Vibration and sound signal analysis, Fast Fourier transform, Dominant frequency extraction

1. INTRODUCTION

The increasing consumption of petroleum poses a serious threat to the environment with the problem of global warming, therefore wide-ranging automotive manufacturers focus on producing hybrid electric vehicles (HEV) while gaining the advantages of both pure electric vehicles (EV) and traditional internal combustion engines. However, the noise and vibration produced during the HEV operation reduce the comfort of the passengers. They also cause stress, fatigue, and adversely affect the drivers [1, 2].

Nowadays, the disruptive innovation of electric vehicles has received a huge pinnacle of attention in the present global situation for several decades. A trend of its popularity has occurred intermittently, however it still cannot be used as a replacement for internal combustion engine vehicles due to price factors, battery quality and performance (mileage per charge), the limited number of available electric vehicle models, as well as the value for resale. The popularity of engine vehicles can be divided into 3 periods as follows.

First of all, the beginning popularity occurred in 1993, the state of California of the United States announced the zero-emission vehicle standards. Owing to the vehicle performance limitations, however, the developed vehicle remains unpopular.

The second wave of popularity resurfaced in 2010 with the introduction of Tesla's Roadster, Mitsubishi's i-MiEV, and Nissan's Leaf models. Limitations of 200 km on a single charge and the number of public charging stations caused difficult decisions for the consumers.

The 3rd trend of popularity from the year 2017 until the present is caused by the problem of cumulative air pollution. The combustion of internal combustion engine vehicles has various polluting effects. Greenhouse gases, dust, and exhaust gases cause global warming and more severe disasters. The agreement in the Paris treaty (COP-21) to reduce greenhouse gas emissions by 20-25% by 2030, the advances in materials science technology development, and the better battery efficiency provoked the prevalence of the new electric vehicle popularity. Electric vehicles are expected to be sold at prices comparable to those of conventional cars in the same performance [3].

In addition, noise, vibration, and harshness (NVH) issues affect the retina and visible objects, resulting in a blurry view of the drivers. In addition, competition in the automotive market is required to have a vehicle's acoustic and vibration dampening properties for optimal performance [4].

From the previous study, the analysis of vibration and sound signals has been inaugurated and developed for many years. The external and internal factors which affect the working conditions of the vehicles have been continuously performed. One study of the environmental effects of the road surface type and condition on the traffic flows management mode in the case of directive management has been explored by Novikov et al.,

[5]. Its focus is the method of assessment of the effect of the road surface type and condition on the capacity rate of the signalized area and therefore its effects on the traffic flow management mode. It has been concluded that there is a correlation between the friction coefficient and the capacity of the managed area resulting in the change of the traffic lights cycle, which is also corroborated by the conducted field experiment on a signalized intersection.

Another external factor that affects vehicle durability has been conducted by Hu and Zhong in 2019. They applied a conventional finite element model for linear and nonlinear analysis for multibody full-vehicle-durability simulation. Six different kinds of test road surfaces are conducted in the simulation, finally, it has been concluded that the explicit–implicit co-simulation techniques are efficient and accurate enough for engineering purposes [6].

Moreover, the interaction between the type and technical condition of road surfaces, dynamic vehicle loads, and the level of vibration propagated to the environment has been studied by Czech [7]. It has been insisted that the type of road surface and the technical condition and varied dynamic vehicle loads are explicitly affecting the level of vibration propagated to the environment.

A study of the discomfort caused by vibration for three models of micro commercial vehicles running in four types of road conditions has been performed by Huang and Li [8] since the main environmental stress of vibration affected the vehicles implicitly. Another external factor analysis has been conducted by Litak and his colleagues. They investigated the chaotic vibration which was the effect of critical Melnikov amplitude of the road surface profile to a quarter car model [9]. Blekhman and Kremer also conducted a study of the effect of road unevenness on the dynamics of the averaged longitudinal motion of a vehicle [10].

As for internal factor analysis, a study of detection and diagnosis of the faults in rotating machinery, a number of the mechanical vibration-based studies have been tremendously pursued [11-13. Inspecting the associated signal processing for machine diagnosis, an amount of research on signal processing adaptation has been investigated for fault diagnosis [12]. The discrete wavelet transform (DWT) in the temporal and spatial domain was successfully applied with the vibration signal for the engine fault diagnosis of the diesel engine and the gearbox [12, 13]. The other successful techniques of the power spectrum analysis with high order, cepstrum analysis, and neural network approach were utilized for fault diagnosis and an indication of some of the specific induction motors [14]. Another interesting applied technique of the Fourier transform has been widely used in signal processing, for example, the Fourier transform coefficients adopted in the features of mel-cepstral HMM-based speech modeling for speech synthesis [15]. It is consequently adapted to the correlation analysis of vibration and sound signals for a gasoline-engine car [16]. Moreover, the power of signal analysis with less time consumption and the low computational cost was conducted in a comparative study of LPG-modified engine and normal oil-usage engine [17], and also in a fault diagnosis of rolling element bearings [18]. Another internal analysis has been introduced, the problems of gasoline substitution with LPG boiling system installation cause some significant variation in vibration and sound signals of the modified engines [19-22]. Subsequently, some analysis techniques of the vibration and sound signals were proposed to differentiate between the LPG-modified engine and the conventional gasoline engine, subsequently, some significant attributes were used to indicate the irregularities of the corresponding engines [23-24]. Another internal factor study of vibration and sound signal analysis for a gasoline engine with LPG-installation and some specified fault simulations was investigated, LPG-installation and the specified faults concretely affected the engine efficiency degradations [25-27]. Moreover, an analysis of vibration signals inside a personal gasoline-engine car driving upon three types of roads including paved road, concrete road, and gravel road, has been addressed [28].

This paper applies engineering knowledge to analyze the vibration and sound of an HEV and an EV from the worldwide manufacturers by using the similar technique applied with the LPG-modified gasoline engine [27] and also deploying the instrument setting from the analysis of vibration signals inside a personal gasoline-engine car [28]. The analysis applies driving at different engine speeds at three different positions within the passenger room to evaluate the quality of service comparatively.

A couple of principle purposes are to compare the vibration and sound signal attributes with three different measuring positions and different engine speeds for both models. The Fast Fourier Transform (FFT) is adopted to extract the signal spectrum and the corresponding features in the analysis procedure [6, 19, 20, 29].

2. RESEARCH SIGNIFICANCE

The NVH of HEVs and EVs are the most important factors for automotive manufacturers to meet the perceived product quality requirements. The original factors of NVH are the vibration and the dynamics of vehicle drivetrains, however the external factors such as wind conditions and road conditions are also contributed to the problem of the

Fig.1 HEV car of Honda Accord hybrid (DOHC) i-VTEC Y2015 model.

Fig.2 EV car of FOMM ONE Y2018 model.

NVH issues. The vibration and sound analysis presented in this study is the fundamental procedure to the development of vehicle structures and materials to manage the reduction of vibration and sound transmitted to the users.

3. MATERIAL AND METHODS

In this section, the HEV and the EV have been generally explained in principles. The tested personal HEV car is of the Y2015 Honda Accord hybrid (DOHC) i-VTEC model with a 2.0-liter engine, 4 cylinders, and 16 valves. Meanwhile, the tested EV car is of the FOMM ONE Y2018 model with a gross battery capacity of 11.84 kWh, the system power of 14 Hp. These models have been selected in this study due to their popularity as depicted in Figs. 1 and 2, respectively. The experimental procedure has been illustrated step by step. Finally, the experimental setups have been therefore presented.

3.1 Hybrid Electric Vehicles

The hybrid electric vehicle is defined literally as a vehicle that uses oil and electricity. The HEV engine room of an experimental specimen is partly depicted in Fig. 1. The energy from the oil has been partially converted to electricity stored in a specific type of rechargeable battery. It is aimed at reducing combustion engine consumption, reducing pollution, reducing internal vibration, and also saving total fuel consumption [1].

The term “hybrid” means the combination use of both the conventional internal combustion engine and the electric motor in the vehicle system process. In the electric charging subprocess, the generated electrical energy while the engine braking period slows down is stored in the battery. On the other

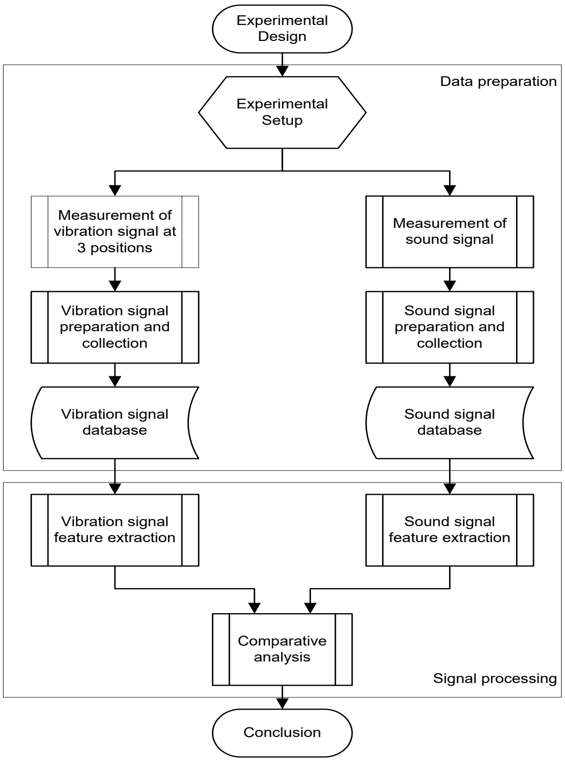
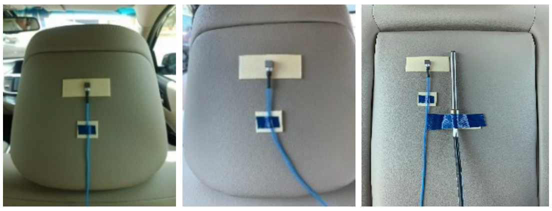


Fig.3 Experimental Procedure.



(a) (b) (c)

Fig.4 Allocation of three vibration sensors and a condenser microphone: (a) the right front, (b) the left front seat, and (c) the rear seat.

Fig.5 Allocation of the NI rack.

hand, during the EV-drive mode, the stored energy is released to run the drive motor without the fuel consumption. In addition, the reduction in fuel consumption occurs when the engine is always running at the optimal engine speed. In summary, when the vehicle's energy demand is greater than the volume that the engine produces, the vehicle is supplementarily powered by an extra battery [2, 4]. The driving modes of the HEV are concluded as follows.

The EV-drive mode: the vehicle is powered by electric power from a Lithium-ion battery via an electric motor.

The hybrid-drive mode: the engine and electric motor work together with good acceleration. While the accelerator pedal is being released, the engine stops working.

The engine-drive mode: the engine drives all of the power directly to the front wheels without using electric power.

The sports-drive mode: the engine sends all the power directly to the front wheels but gives a higher rpm than normal operation. This mode is ignored since it is rarely used in practical use.

3.2 Electric Vehicles

This type of car uses only electric power to drive the whole body. The way a pure electric vehicle works is not as elaborate and complex as a petrol car. There are only three main driving components contributing to the efficiency of driving. These three components include a battery, an inverter, and an electric motor.

3.3 Experimental Procedure

The experimental procedure consists of a couple of consequential stages of data preparation and signal processing sub-procedures as depicted in Fig. 3. A brief explanation of the procedure is presented as follows.

Initially, the experimental design process has been performed. All experimental equipment includes a number of vibration sensors and their accessories, a condenser microphone and its complementary parts, an NI card for interfacing with a computer, and a computational program for signal processing.

At the data preparation, the experimental setup is conducted to retrieve the vibration and sound signals simultaneously from the experimental car with a number of engine speeds. Thereafter, the measurement, preparation and collection, and database implementation are performed respectively. The vibration and sound signal retrieving setups have been arranged during the experimental setup process. Three sets of high-frequency vibration sensors and a condenser microphone are allocated at different positions within the passenger room. The corresponding signals are then transferred into the processing computer through a group of NI interfacing cards. The sensors are allocated at three positions including at the right front, the left front seat, and the rear seat as depicted in Fig. 4(a), 4(b), and 4(c). Three vibration sensor wires and the microphone wire are connected with the NI cards which are attached with the NI rack as depicted in Fig. 5. The rack is also connected to the computer which the signals are retrieved into the Labview program.

At the signal processing, the feature extraction and comparative analysis are performed respectively. The signal analysis technique of Fast Fourier transform has been applied with all of the portions of the vibration signals for all groups within the database to obtain their corresponding frequency spectrum. From the output frequency spectrum, the most dominant peak appearing in the frequency domain is extracted. The frequency and magnitude at the peak are analyzed. Monitoring the frequency spectrum brings about some frequencies at the dominant peak points and their corresponding amplitudes. These highest peaks are assumed to represent the important components of the vibration signal inherited from the movement of the vehicles. These extracted features are consequently utilized in the final process of the comparative analysis.

4. EXPERIMENTAL RESULTS

In the signal feature extraction process, the FFT technique has been adopted to extract the significant features as described in the previous studies [15, 25, 26]. The extracted features are consequently utilized in the final process of the comparative analysis using the statistical averaging technique. The comparative graphs are constructed and presented in this section.

4.1 HEV Analysis

As for vibration comparative analysis, the comparisons of the averaged magnitude of emerging peak of the frequency spectrum of the vibration signal measured at three different positions in gravitational acceleration unit (g) with different engine speeds for three operating modes are presented in Figs. 6-8. On the other hand, the comparisons of the averaged magnitude of the emerging peak of the frequency spectrum of the vibration signal measured at three operating modes in gravitational acceleration unit (g) with different engine speeds for three different positions are presented in Figs. 9-11.

As for sound comparative analysis, the averaged magnitude of the emerging peak of the frequency spectrum of the sound signal measured of three operating modes at the rear seat has been plotted and presented in Fig. 12.

Based on the previous study of an analysis of vibration for a gasoline-engine car driving on three types of roads [28], the results are analyzed accordingly. From Figs. 6-8, the averaged

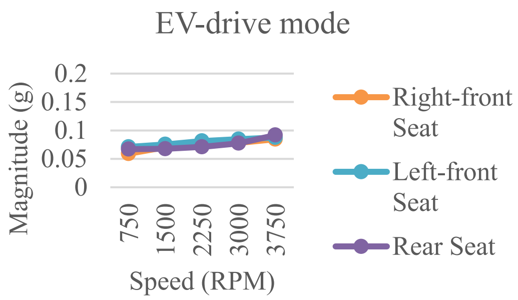


Fig.6 The averaged magnitude of emerging peak of the frequency spectrum of the vibration signal measured at three different positions of EV-drive mode.

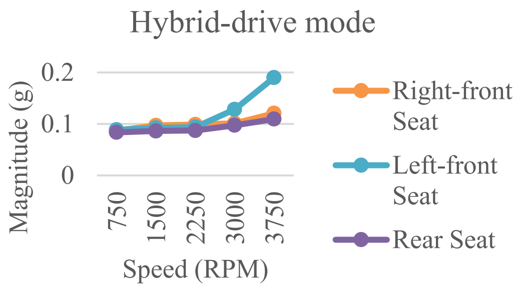


Fig.7 The averaged magnitude of emerging peak of the frequency spectrum of the vibration signal measured at three different positions of hybrid-drive mode.

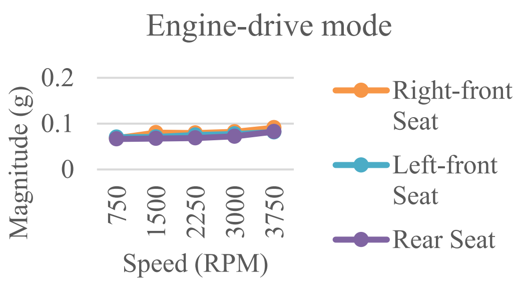


Fig.8 The averaged magnitude of emerging peak of the frequency spectrum of the vibration signal measured at three different positions of engine-drive mode.

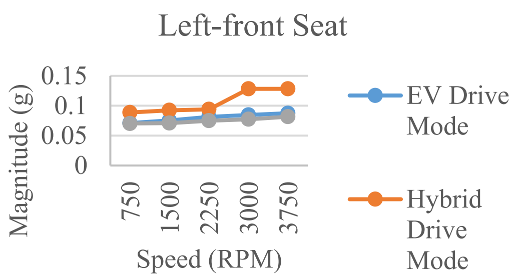


Fig.9 The averaged magnitude of emerging peak of the frequency spectrum of the vibration signal measured of three operating modes at the left-front seat.

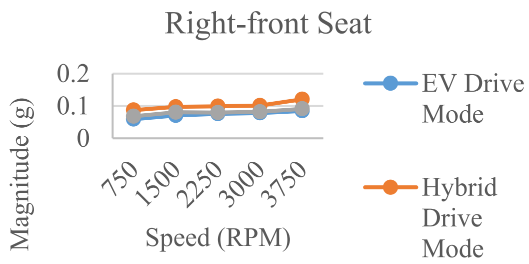


Fig.10 The averaged magnitude of emerging peak of the frequency spectrum of the vibration signal measured of three operating modes at the right-front seat.

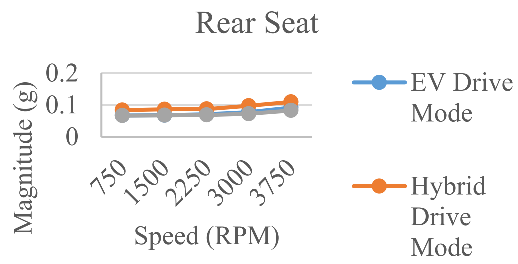


Fig.11 The averaged magnitude of emerging peak of the frequency spectrum of the vibration signal measured of three operating modes at the rear seat.

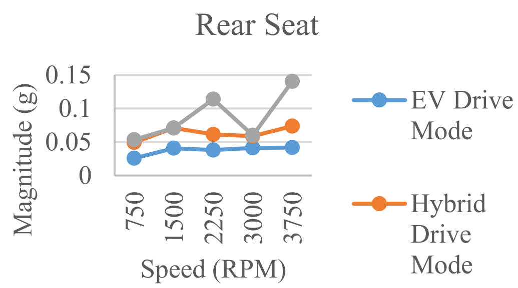


Fig.12 The averaged magnitude of emerging peak of the frequency spectrum of the sound signal measured of three operating modes at the rear seat.

magnitude of the emerging peak of the frequency spectrum of the vibration signal increases while the engine speed is being raised. This finding is highly consistent with the result of the previous study.

From Fig. 6 with focusing on the EV-drive mode, the averaged magnitude of the emerging peak of the frequency spectrum of the vibration signal increases while the engine speed is being increased. The left-front seat reflects the highest impact to the averaged magnitude when comparing with the others. Furthermore, it can be noticed that the magnitude of the rear seat emerges as the highest value when the speed arrives at 3750 rpm.

From Fig. 7 with focusing on the hybrid-drive mode, the averaged magnitude of the emerging peak of the frequency spectrum of the vibration signal increases while the engine speed is being raised as same as that of the EV-drive mode illustrated in Fig. 6. It can be seen that the magnitudes of the left-front seat trends to increase much more than those of the others.

From Fig. 8 with focusing on engine-drive mode, the averaged magnitude of the emerging peak of the frequency spectrum of the vibration signal has the same movement along the engine speed axis with an increasing upward trend. The magnitude of the right-front seat noticeably tends to increase more than those of the others.

From Fig. 9 with focusing on the left-front seat, the averaged magnitude of the emerging peak of the frequency spectrum of the vibration signal increases while the engine speed is being raised for all of the vibrations at all operating modes of the HEV. The hybrid-drive mode gives the highest level to the averaged magnitude when comparing with the others, meanwhile, the engine-drive mode gives the least level.

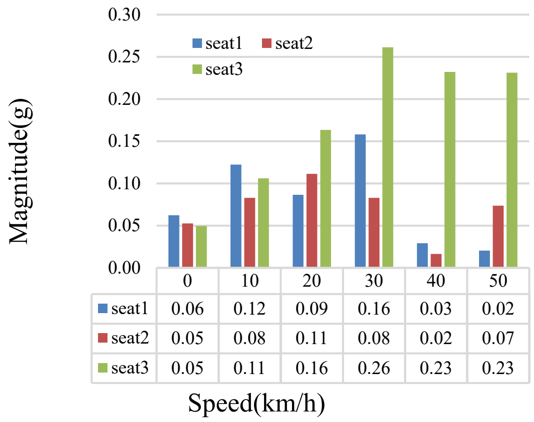
From Fig. 10 with focusing on the right-front seat, the trends of all averaged magnitudes are as same as those of the left-front seat in Fig. 8. However, it has been seen that the EV-drive mode gives the least level among all operating modes.

From Fig. 11 with focusing on the rear seat, the trends of all averaged magnitudes are closely similar to those of the left-front seat in Fig. 8.

From Fig. 12 with focusing on the sound signal to which the microphone is attached at the surface of the rear seat, the trends of all averaged magnitudes are closely similar to those of the right-front seat in Fig. 10.

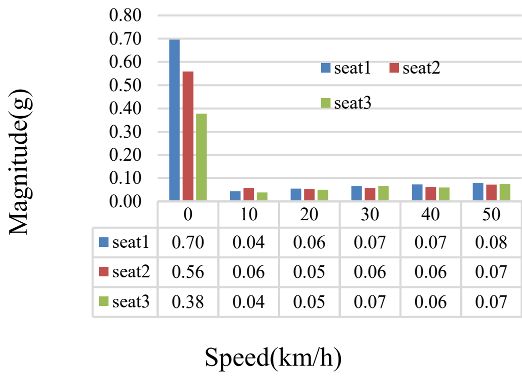
4.2 EV Analysis

As for vibration comparative analysis, the comparisons of the averaged magnitude of emerging peak of the frequency spectrum of the vibration signal measured at three different positions in gravitational acceleration unit (g) with different engine speeds are presented in Fig. 13. As for sound comparative analysis, the averaged magnitude of the emerging peak of the frequency spectrum of the sound signal measured at three different positions with different engine speeds has been presented in Fig. 14. From the experiment results, it can be observed from Fig. 13 that when the engine speed of the EV car is raised until reaching 30 km/h, the averaged magnitude of the emerging peak of the frequency spectrum of the vibration signal trends to increase.



	0	10	20	30	40	50
seat1	0.06	0.12	0.09	0.16	0.03	0.02
seat2	0.05	0.08	0.11	0.08	0.02	0.07
seat3	0.05	0.11	0.16	0.26	0.23	0.23

Fig.13 The averaged magnitude of the emerging peak of the frequency spectrum of the vibration signal measured at three distinct positions.



	0	10	20	30	40	50
seat1	0.70	0.04	0.06	0.07	0.07	0.08
seat2	0.56	0.06	0.05	0.06	0.06	0.07
seat3	0.38	0.04	0.05	0.07	0.06	0.07

Fig.14 The averaged magnitude of the emerging peak of the frequency spectrum of the sound signal measured at three distinct positions.

accordingly for all three different positions. After that, the average magnitude gradually decreases. Moreover, comparing among three different positions, the averaged magnitudes of emerging peaks at the left-front seat (seat 1) are higher than those of the other positions for the first two speeds (0 and 10 km/h), meanwhile, the averaged magnitudes of emerging peaks at the rear seat (seat 3) are mostly highest than those of the other positions for the other four speeds (20 to 50 km/h).

On the other hand, it can be seen from Fig. 14 that when the engine speed of the EV car is raised from 10 km/h to 50 km/h, the averaged magnitude of the emerging peak of the frequency spectrum of the sound signal trends to increase accordingly for three different positions. The averaged magnitudes of emerging peaks at the standstill (speed of 0 km/h) are at the highest levels compared with those of other speeds for three different positions. Moreover, comparing among three different positions, the averaged magnitudes of emerging peaks at the left-front are mostly higher than those of the other positions, meanwhile, the averaged magnitudes of emerging peaks at the rear seat are mostly lowest than those of the other positions.

5. CONCLUSIONS

An analysis of vibration and sound signals of a HEV and EV cars with three different operating modes at three different positions within the passenger room has been initiated. For HEV analysis, the comparison of the vibration affecting from all three operating modes with three different measuring positions has been addressed. As for the vibration analysis with positioning focus, the left-front seat presents the highest levels of averaged magnitudes for EV-drive mode and hybrid-drive mode, meanwhile, the right-front seat shows the highest levels of averaged magnitudes for engine-drive mode. As for the vibration analysis with operating mode focus, the hybrid-drive mode gives mostly the highest levels of averaged magnitudes for all sensor positions. The comparison of the sound affecting from all three operating modes has been accomplished. As for the sound analysis, the engine-drive mode reflects the highest levels of averaged magnitudes for operating modes. Concentrating on varying engine speeds, the levels of vibration and sound magnitudes directly vary with the engine speed. The study summarizes that the proposed analysis technique of vibration and sound signals can be used to distinguish the signal features of all scenarios of an HEV car.

For EV analysis, as for the vibration analysis with positioning focus, the averaged magnitudes of emerging peaks at the left-front seat are higher than those of the other positions for the first two speeds (0 and 10 km/h), meanwhile, the averaged magnitudes of emerging peaks at the rear seat are mostly highest than those of the other positions for the other four speeds (20 to 50 km/h). As for the sound analysis, the averaged magnitude of the emerging peak of the frequency spectrum of the sound signal trends to increase accordingly for three different positions. The averaged magnitudes of emerging peaks at the standstill are at the highest levels compared with those of other speeds for three different positions. For further interest, the other popular types of electric vehicles and improved signal processing techniques will be studied.

6. ACKNOWLEDGMENTS

The study was supported by the Faculty of Engineering at Sriracha. The associated equipment was arranged by the members of Mechanical System and Signal Processing research group.

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