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ORIGINAL ARTICLE

Validation of Clicking-type Noise and Vibration in Automotive HVAC System

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ABSTRACT – In this study, the characteristics of clicking-type noise and vibration occurring in the automotive heating, ventilation and air conditional (HVAC) systems are investigated. A lab-scale model of HVAC system is developed, and validation is carried out with a vehicle system. A fixed blower speed of 1 (at an airflow of 2.53 m/s) with alternated air conditional (AC) was implied in this study. Three different sensors namely as tachometer, accelerometer, and microphone were used to measure and prove the existing noise in the HVAC system. The study inferred that the compressor contributed significantly to the total vibration and noise in the HVAC system. Other components such as AC pipe, evaporator, and thermal expansion valve (TXV) also contributed to a slight extent. The clicking noise was observed in the operating frequency range of 200 ~ 300 Hz. This noise and vibration issues are partly influenced by the running conditions of the AC and the effect was significant when the AC was turned on. The validation of the findings in the model shows a good agreement with the results obtained in the vehicle system, whereby the clicking noise and vibration can be observed at a similar frequency range.

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INTRODUCTION

In the 1980s, the sound and vibration of the vehicle became an interesting area that attracted the attention of researchers and manufacturers in the automotive industry. Every component in a vehicle has an explicit function, which also accompanied by the production of distinctive noise and vibration levels [1]. Although these factors were not seriously considered, they eventually defined the customer's comfortability and reliability [2]. Some of the features that been upgraded in the evolution of vehicle comfort are the motor of power window [3] and seat adjustment function [4]. Apart from these, heating, ventilation and air conditional (HVAC) system had a more significant impact on the vehicle, especially during the running conditions. The HVAC system can be operated in two conditions (i.e., manual and automatic). The manual mode works based on the requirements and settings preferred by the rider with respect to the speed, temperature and humidity. The automatic mode senses the thermal situation inside the vehicle and automatically adjusts the parameters of heating, ventilation and cooling as well as the compressor state (i.e., turned on or off). However, incorporating multiple functions with different HVAC components have increased the noise and vibration generated in the vehicle [5, 6]. Thus, the need to understand the system and its impact on the HVAC components should be emphasised.

Computational fluid dynamics (CFD) has been proved to be effective in predicting noise behaviour in different applications. For HVAC system, most of the research was concentrated on the noise coming from the ducting. This component is crucial because it acts as a pressure-driver for flow separation and flows around obstacles. Detailed studies with experimental and simulation evidence have been reported elsewhere [7–9]. Jäger et al. considered five 'in-demand' vehicle brands for the ducting test to study the unsteady flow through the system components that become the sources of the aerodynamic noise [10]. Two different numerical approaches, namely as finite volume method (FVM) and Lattice Boltzmann method (LBM) were compared in the study. The result shows that both approaches were in good agreement in terms of time-averaged flow structure, but against the experimental results [11, 12]. Wang et al. suggested that a complete model that imitated the real operation could counter this issue [13]. The study also revealed that covering the motor vent passage hole and sealing the weld gap does not affect the total noise level. However, it does reduce the spectral noise peaks at the blade passing frequencies and affected the cavity resonance peaks. Another study suggested that by using the model developed, the dynamic characteristics such as natural frequencies and mode shapes of the individual components were able to be determined [14].

Characterisation of the noise and vibration from the HVAC system components are least reported in the literature. Despite this fact, there are some prelusive studies on the characterisation of several noises namely as air-rush, hissing, humming, and clicking. The air-rush noise existed when the air is flown between the outlets with the turbulence effect [15] and it can be heard from the blower [9, 14]. The hissing noise is an audible noise that is mainly produced by the evaporator pipe inlet. Satar et al. [14] experimented with two operating conditions (i.e., idle and tracking) and found that the noise was produced at the frequency range of 4000-6000 Hz for both conditions. The noise is generated due to the forcing flow of the refrigerant through a small orifice area. Similarly, the humming noise can be found in the vehicle's

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interior space and the investigation has been conducted for both idle and running engine conditions. From the result, a power steering pump shows the most significant noise contributor which detected at 300-350 Hz and 150-250 Hz for idle and running engine conditions, respectively [16]. Another study identified the existence of two or more contributions from the compressor and AC pipe. The authors highlighted that the vibration generated was transferred in sequential from the compressor until the evaporator [14]. The study found that the clicking noise is presented in the frequency range of 200 ~ 300 Hz, but no validation has been carried out with the vehicle system, which doubts the reliability of the results. The study also indicated that the clicking noise can be induced from the compressor of the HVAC system during the engagement and disengagement process (turning of low to high air pressure and vice versa). Nevertheless, the study involving this type of noise is limitedly available.

This study proposed a lab-scale model of the HVAC system, which consists of real HVAC components attached to a rig structure. The model imitates the real operation of the HVAC system and offers a detail study to investigate the presence of the clicking noise. The validations are carried out using sound diagnosis and real vehicle HVAC system.

METHODOLOGY

The study comprises three main stages: problem identification, evaluation, and validation. Figure 1 shows the flowchart of the methodology adopted in the individual stages to investigate the presence of the clicking noise in the HVAC system. The problem is initiated by identifying the presence of the clicking noise through a subjective feeling, which is considered the problem. In the evaluation stage, the measurement is carried out on the suspected location. The noise produced is related to the corresponding vibration from the system components. The components that produced a significant effect (extent of noise and vibration) are considered suspected noise sources.

Validation is carried out based on two approached, firstly with a sound diagnosis and a real vehicle system. The sound diagnosis is aid from the audio recognition to determine the frequency range containing the clicking noise and exact location of the noise sources. Meanwhile, the vehicle level is a real system of the HVAC system, where it provides reliable data for the comparison with the model system. The validation from both methods is required to determine an exact frequency range of the clicking noise and its contributor. A good consensus between the measurement and both methods can be regarded as a 'Yes' condition and oppositely for a 'No' condition.

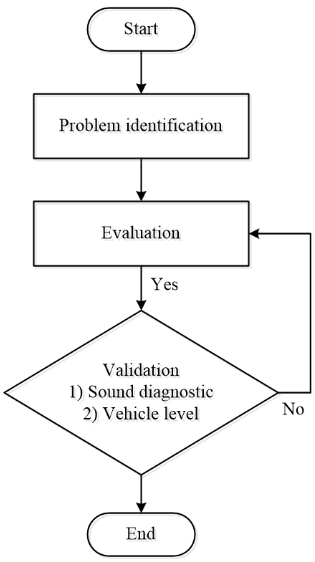
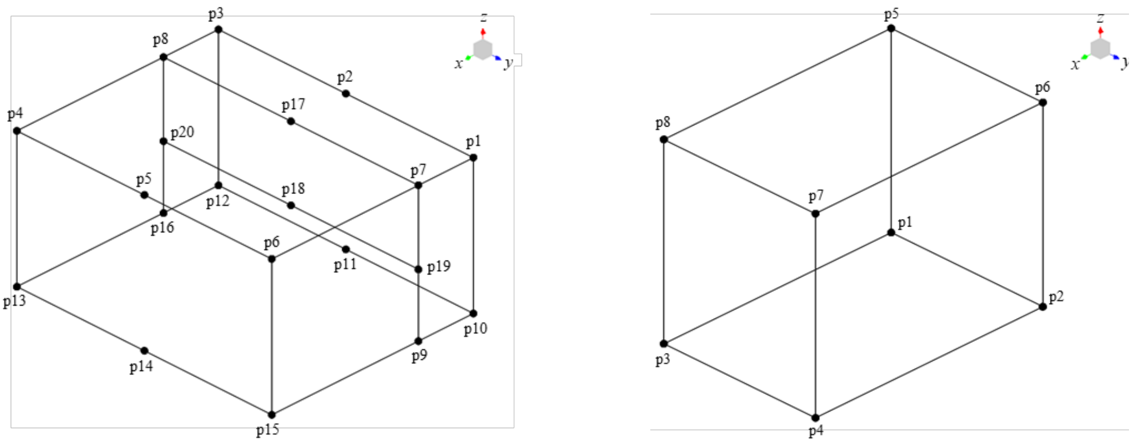


Figure 1. Flowchart in determining the clicking noise.

Experimental Modal Analysis

The experimental modal analysis (EMA) is carried out to determine the dynamic characteristics of the targeted component. The analysis consists of geometric modelling and impact testing. The dimensions of the targeted structure were measured and modelled, as presented in Figure 2. Figure 2(a) and (b) show the models of rig structure and compressor, respectively. A total of 8 and 20 nodes were used to define the overall shape of the compressor and rig structure. In the testing, an impact hammer (Kistler, 9724A5000) was used to hit the node vertically and orderly, which served as the input force to excite the structure. The response was measured by an accelerometer (Dytran, 3055B2T) that was placed at one of the node locations. The signals from the instruments were captured by the data acquisition system (LMS SCADAS) with the integration of the LMS Test.Lab software.

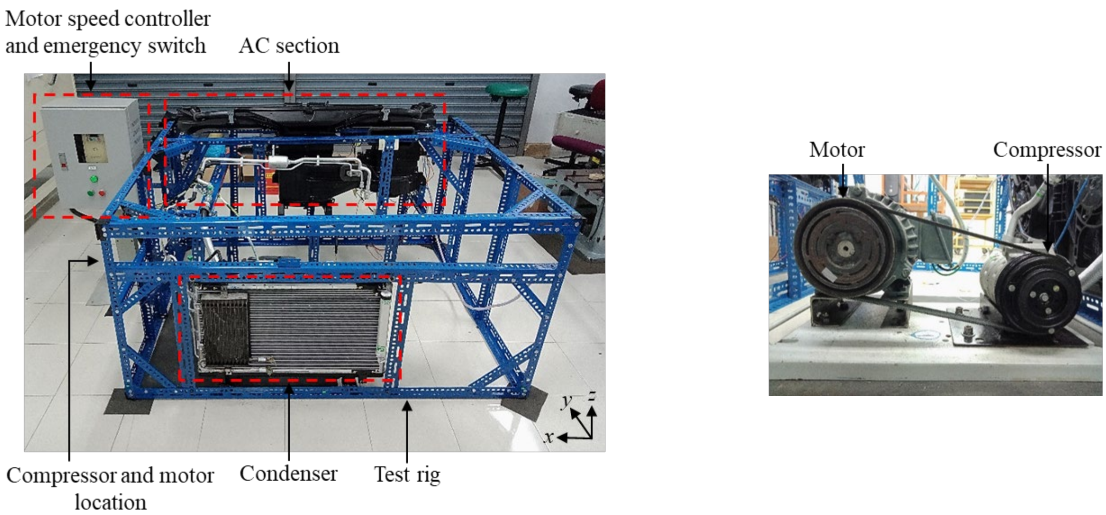


(a) (b)

Figure 2. Geometry models of the (a) rig and (b) compressor structure.

Design and Implementation of the HVAC Lab-scale Model

The components of the HVAC system were assembled entirely and firmly to a rig structure, as shown in Figure 3(a). The rig, with a solid rigid structure, acts as the base of the HVAC system. On this base, a motor that coupled with a compressor shown in Figure 3(b) was used to drive the system and connected using a belt transmission. The compressor was used to draw the low-pressure vapour from a thermal expansion valve (TXV) and changes the state of vapour to high-pressure conditions. The pressurised vapour subsequently flows through the condenser and the receiver. The high-pressure vapour undergoes a condensation process, wherein it is converted to a high-pressure liquid by releasing the heat. The radiator fan was used to reduce the heat by blowing the heat out of the system. The high-pressure liquid then flows to the drier, which absorbs the moisture that enters the AC system. Again, the liquid flows towards the TXV to undergo a pressure reduction. Before entering interior space, the evaporator absorbs the heat from the air and convert it to low temperature and low-pressure vapour, when the AC is turned on. The main function of the blower is to emit air to the vehicle's interior space and circulate air through the vent in the centre. The centrifugal forces were used to fling the air outwards in one direction. The entire sequence of processes was repeated as a continuous cycle, while cold air was spread to the interior space of the vehicle.



(a) (b)

Figure 3. (a) Full view of the HVAC model and (b) motor-compressor arrangement.

Experimental Setup of Model and Vehicle HVAC Systems

The operating speed of the motor and engine in the model and the vehicle systems were set at 850 rpm, respectively. Figure 4 shows a tachometer (BSWA, MA231) used to measure the motor rotational speed in order to set and regulate as per vehicle engine speed. The individual vibration response produced by components was measured by the accelerometers (Kistler, 9724A5000). The locations of mounted accelerators on the model and vehicle HVAC systems are shown in Figure 5 and 6, respectively. The accelerometers were mounted on the suspected components, namely as compressor, evaporator and TXV using the wax. These sensing devices were also connected to LMS Test.Xpress software which is used to collect and record the acceleration produced.

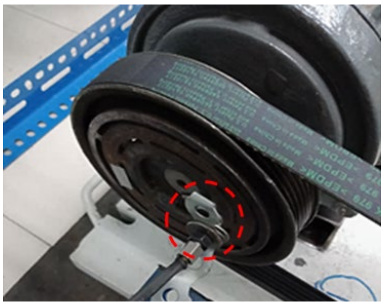
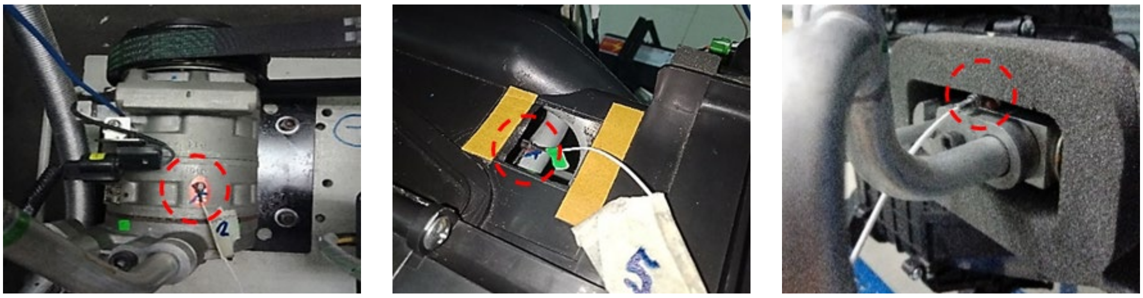
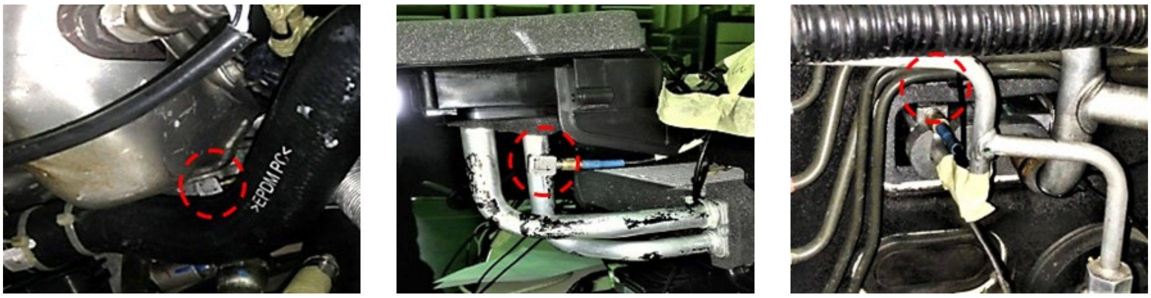


Figure 4. Tachometer attachment to the compressor of the model system.



(a) (b) (c)

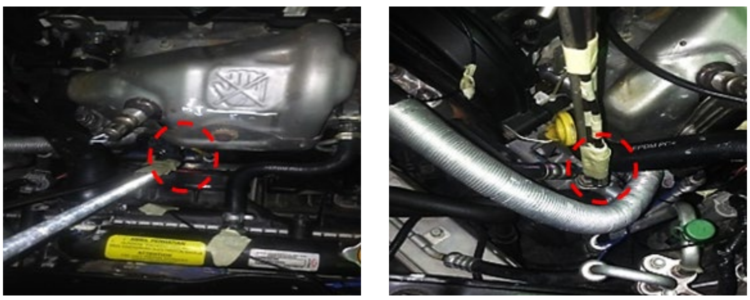
Figure 5. Location of the accelerometer on (a) compressor, (b) evaporator, and (c) TXV of the model system.



(a) (b) (c)

Figure 6: Location of the accelerometer on (a) compressor, (b) evaporator, and (c) TXV of the vehicle system.

The data obtained from the model was preliminary evidence and needed to be verified. A sound diagnosis using a microphone (BSWA, MA231) is then been conducted. The microphones are placed at an offset distance of 10 cm from the suspected components in both systems (Figure 7). The sensors are connected to LMS Test.Lab Acoustic software, which processes the measured noise. The exact noise detection is performed by applying frequency filters on the audio track, which determines the exact frequency range of the clicking noises. The noise that being tracked has an identical and comparable characteristic with that of the subjective hearing before specifying the frequency range of the filter from the sound recorded. The frequency range of interest is selected within 0~500 Hz since it is the most sensitive audible range for the human ear, based on the study by Sah et al. [17]. There are two conditions of AC investigated in this study, i.e., ‘off’ and ‘on’ alternately. The air is flowed from the blower at a low speed of 2.53 m/s and maintained, as it may generate other types of noise.



(a) (b)

Figure 7: Position of the microphone near the (a) compressor and (b) power steering of the vehicle system.

RESULTS AND DISCUSSION

EMA Results

Figure 8(a) and (b) show the frequency response function (FRF) of the rig structure and compressor in the frequency range of 0 ~ 500 Hz, respectively. Table 1 highlights the corresponding natural frequencies and mode numbers. From the figures, the rig structure has five peaks of natural frequencies and higher mobility output was obtained for the third mode compared to the other four modes. On the contrary, the compressor had only three peaks, with the highest output in the second mode. From this result, it can be inferred that the components have a considerable amplitude of vibration when operating close to the natural frequencies, particularly in the range of 250~350 Hz. Studies by Scheillemeit et al. [18] and Rodarte et al. [19] reported similar results implying that they were typical for these systems.

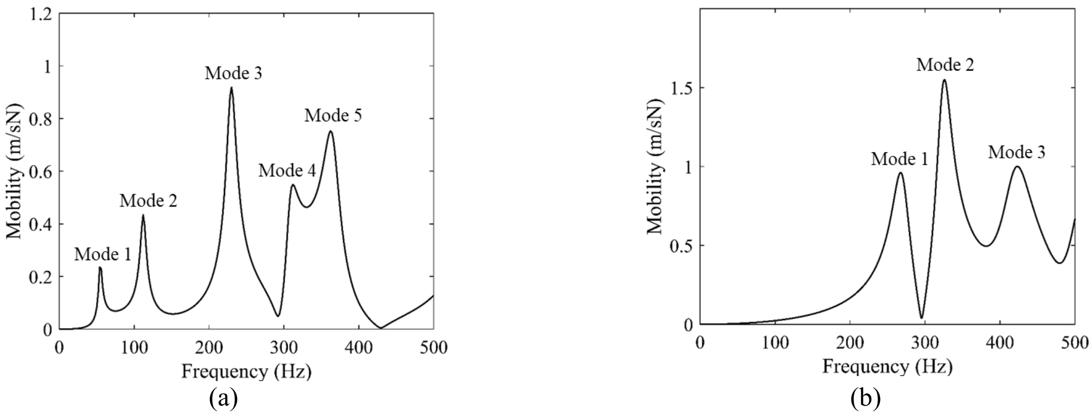


Figure 8. FRFs of (a) rig structure and (b) compressor of the HVAC model.

Table 1. Dynamic characteristics of the structures in the HVAC model.

	Mode (Hz)				
	1	2	3	4	5
Rig structure	56.66	112.23	229.60	307.56	365.02
Compressor	99.76	290.81	365.14	N/A	N/A

Vibration Spectrum Result

Figure 9 shows the correlation between the vibration and clicking noise-induced among five major components in the HVAC model system. The compressor had experienced the highest acceleration of approximately 0.05 m/s^2, which was considerably higher than motor, AC pipe, TXV and evaporator pipe inlet, as observed in the range of 200~300 Hz. The vibration contribution from the motor is neglected since it is only used to drive the compressor.

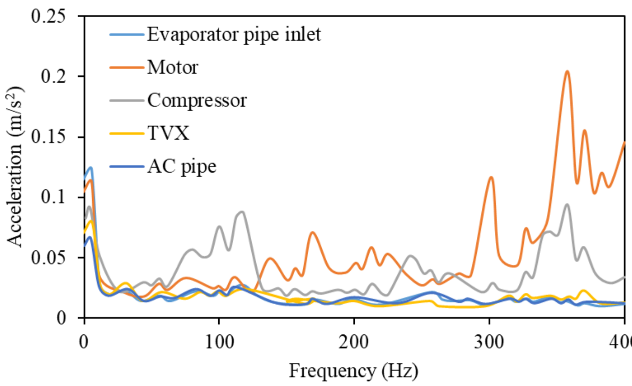
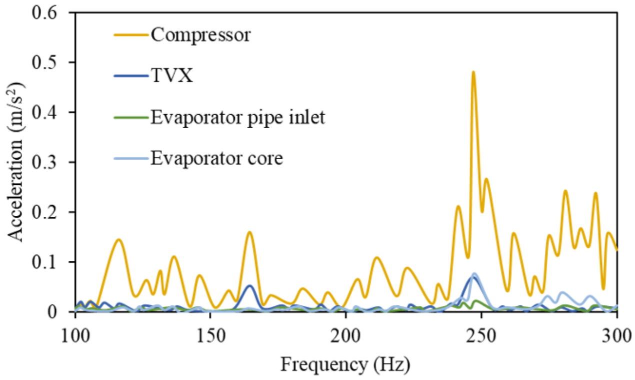
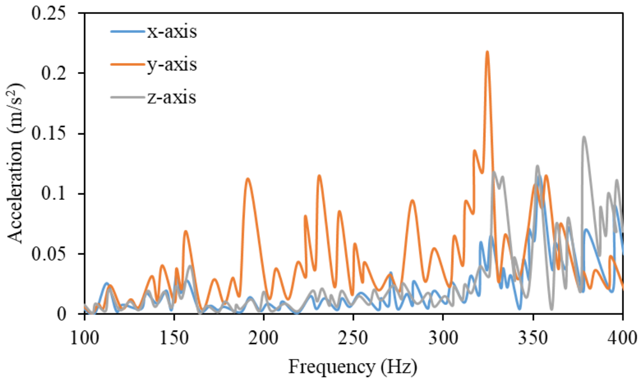


Figure 9. Major vibration contribution of components in the HVAC model system.

On comparing with the vehicle system in Figure 10(a), it is noticed that the peak of the compressor clearly dominated in terms of vibration that contribution in the same frequency range as in the model system. The acceleration of the compressor reached up to a maximum of 0.5 m/s^2, which was very much higher than evaporator and TXV. A thorough investigation of the vibration frequency domain of the compressor is presented in Figure 10(b). In comparison between three directions, the vibration contribution is strongly evident in one direction, i.e. in the *y*-axis direction. It is noticeable that the vibration response increased, particularly in the range of 300~350 Hz and the highest excitation could be attributed to the natural frequency of the respective components. For example, consider the FRF graph of the compressor shown in Figure 8(b), it is reasonable to say that the major source of vibration originated from the compressor, which is the core unit of the HVAC system and then been propagated to the other components. Several researchers also associated the compressor with the generation of other types of noises [20, 21].



(a)

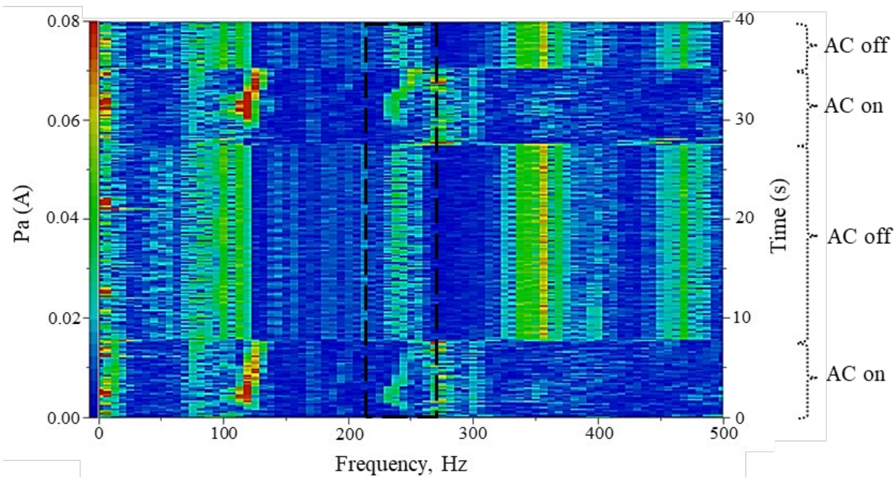


(b)

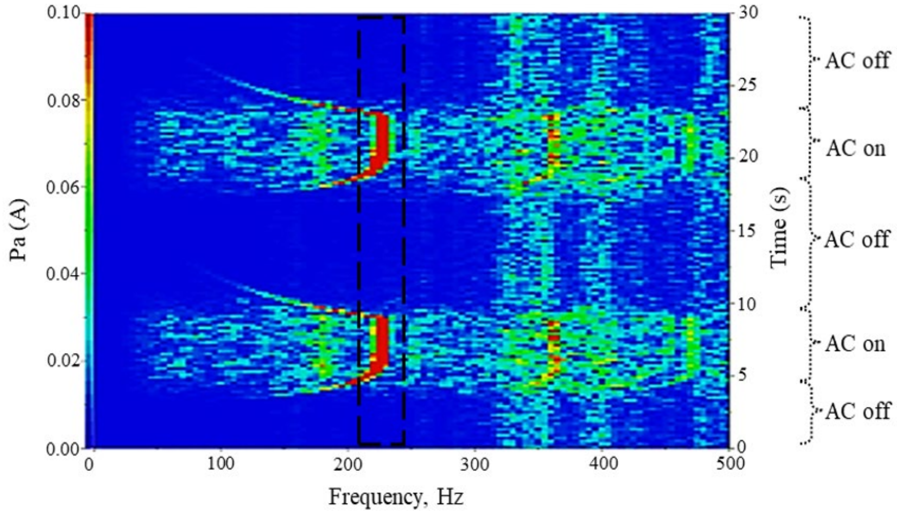
Figure 10. (a) Major vibration contribution of components and (b) individual axis vibration contribution of the compressor in the HVAC vehicle system.

3D Noise Spectrogram Result

Figure 11(a) and (b) show the 3D noise spectrogram results for both compressors (model and vehicle HVAC systems) within the engine running time of 30 s and frequency range of 0~500 Hz. From both figures, the reddish spots are clearly observed in the frequency range of 50~150 Hz, 200~300 Hz and 300~400 Hz when the AC is turned on. The noise spectrogram also witnessed these spots existed towards the frequency of 500 Hz. For both systems, the alternation of AC conditions (on and off) showed a distinct response to the noises. When the AC is turned on, the amplitude of noise grows stronger at 0.06~0.08 Pa(A) and vice versa, as shown in Figure 11(b). The verification using sound diagnosis confirmed that the noise obtained at the operating frequency of 200~300 Hz is the clicking type of noise for both systems. This can be clearly shown in the vehicle system as the clicking noise of the model system is slightly disturbed by the other noise that induced from the motor.



(a)



(b)

Figure 11. 3D noise spectrogram for the (a) model and (b) vehicle HVAC compressors.

The occurrence of clicking noise can be explained further by the effect of engagement and disengagement of the compressor clutch. Figure 12 shows the exploded view of various parts in a compressor clutch. During the disengagement process, the clutch does not undergo rotation (static), wherein there is no flow or circulation of the refrigerant. Conversely, during the engagement process, the clutch is rotated to transfer the energy from the engine to the compressor by a drive belt. Once the field coil (i.e. an electromagnet) is energised, it draws the pressure plate towards it, locking the rotor pullet and pressurising plate together. This causes the compressor to run, creating pressure and circulating the refrigerant [22, 23]. During the running of the compressor, the sound of operation from the compressor is heard, which is also one of the highest contributors to the noise of the HVAC system. The clicking noise is very dominant, particularly during the engagement process, as shown in the time domain graph of Figure 13. From the figure, the vibration amplitude of the compressor is high during the clutch engagement which translated to the clicking noise.

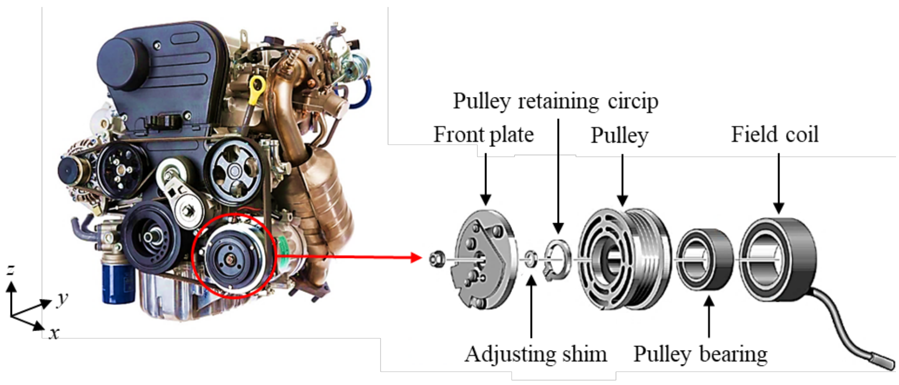


Figure 12. Exploded view of the compressor and its parts.

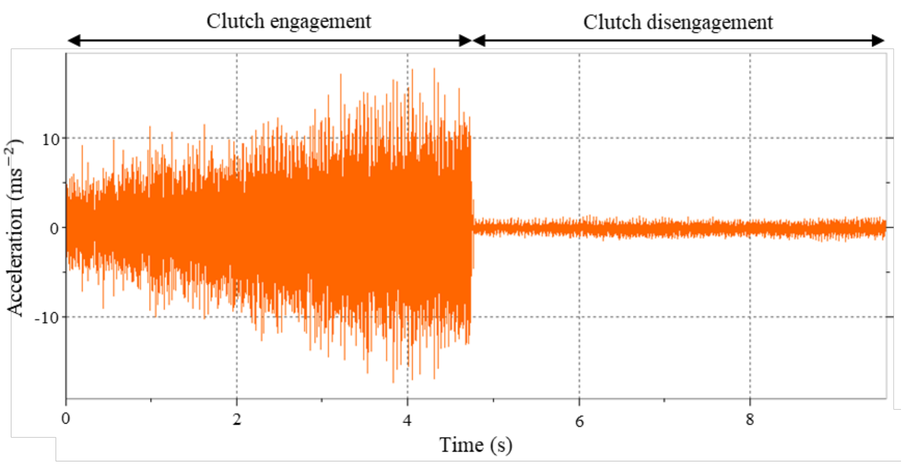


Figure 13. Time-domain vibration response during compressor clutch engagement and disengagement.

CONCLUSION

This paper presents a comprehensive study to investigate the clicking type of vibration and noise that existed in the automotive HVAC system. The development of the lab-scale HVAC model was able to imitate the real vehicle HVAC system and provide a detailed understanding of the root cause of clicking noise and its relationship with vibration. The EMA results clearly showed that the natural frequencies have caused severe vibration amplitude, especially in the compressor. The highest vibration and clicking noise was recorded by the compressor as a result of the periodic engagement and disengagement of the compressor and the clutch. The verification using sound diagnosis has ascertained the presence of clicking noise in the range of 200~300 Hz. The behaviour of the vehicle and model systems concerning the vibration and clicking noise characteristics agreed in terms of the contribution of the individual components and the corresponding frequency ranges.

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