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Technical Note

A Lab-scale HVAC Hissing-type Noise and Vibration Characterization with Vehicle System Validation

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Heating, ventilation and air conditional (HVAC) system provides a cold ventilation for the comfort of the driver and passengers in a vehicle. However, the vibration induced by the HVAC contributes to a reasonable level of noise emission, and hissing is one of the critical noises. So far, the characterization of hissing noise from the vehicle is least to be reported compared to other type of noises. Hence, this paper investigates the occurrence of hissing noise from several HVAC components. A lab-scale HVAC system was developed to imitate the real-time operations of the vehicle HVAC system. Two engine conditions, namely as ambient and operating conditions, were tested at speed of 850 rpm and 850–1400 rpm, with the blower speed maintained constantly at one level. The result shows that the hissing noise from the lab-scale HVAC was produced at frequency range of 4000–6000 Hz. The finding also highlights that the main component contributors of noise emission are an evaporator and a thermal expansion valve. The validation with a real vehicle system showed a good consensus whereby the hissing noise was produced at the similar operating frequency ranges. Also, the hissing noise was found to be louder when in an operating condition which could be taken into consideration by the vehicle manufacturers to improve the HVAC design.

Keywords: hissing noise; HVAC system; vibration; evaporator; thermal expansion valve.

1. Introduction

Vehicle is the most common means of transportation facilitating the movement of people and goods from one place to another. In the developing countries, the role of vehicles is significant in driving the economy. With more vehicles increasing on the roads, most of the people are exposed to noise, especially in urban areas. The roadway noise contributes to a proportionately large share of the total societal noise pollution. The adverse effects include sleep disturbance (Öhrström, 1989), cardiovascular disease (Qatu *et al.*, 2009), and irritation (Žiaran, Chlebo, 2016). Noise emission can also be related to the quality of the vehicle and indirectly affect the preference of customers when considering buying a new vehicle (Shin, Cheong, 2010). Market assessment revealed that noises are one of the third most influential customer concerns about the vehicles after three months of ownership (Kavarana, Rediers, 1999). Generally, all vehicle manufacturers are bound to follow the emission regulation which limits and reduces the noise emission. ISO 362 is an international standard guideline which represents measurement and calculation of the allowable noise level in any type of vehicles. In the vehicle homologation process, it is usually conducted during the design stage, than evaluated by both manufacturer and supplier in compliance with the guideline (ISO 362, 2007). The typical vehicles on the road usually emit an average noise of 72 dBA (Krüger *et al.*, 2016).

The noise types that contribute to the vehicle noise can be classified into three groups: tires and road, engine, and heating ventilation and air conditional (HVAC) noises. Tire and road noises are the typical contributors as a result of contact interaction between tires and road. Due to the effect of adhesion mechanism, tires and road pavements are the significant factors. However, the individual contribution of these mechanisms varies upon conditions, i.e. road paths, driving conditions, and tire type (Seoud, 2019). Horn is another source of noise that was found to have a significant effect within the frequency range of 1000–5000 Hz (Kropp *et al.*, 2012). Engine noise is a vehicular noise that is emitted into the vehicle interior space. This noise mostly radiates from the engine, wherein the combustion processes occurred (Phillips, Orchard, 2001). At constant engine speed, the generation of noise from a petrol engine is lower than diesel engine due to lower in-cylinder pressure excitations (Braun *et al.*, 2013). The presence of this noise created by these two factors has a linear relationship with vehicle acceleration (Sandberg, Ejsmont, 2002). One portion of the noise is also contributed by the HVAC system, which is used to regulate the thermal comfort of vehicle interior space. Several reports on the primary source that contributed to this noise are due to the different characteristics of HVAC related noise that have been proposed.

The different types of HVAC noises are not among the main interest of the researchers, yet, it is important as it has unique characteristics depending on a certain type of noise. Humbad *et al.* (2009) initially found the air rush noise in the HVAC system. The primary source of this noise is a blower that allows air but in a restrictive passage. The air flows across the blades which leads to higher circulation and causes flow reversal. This phenomenon leads to turbulent flows but is unlikely to reach higher noise levels (Humbad, 2001; Hassan *et al.*, 2008). Therefore, Mavuri *et al.* (2008) suggested the influence factors related to the system setting, for example recirculation, full-cold, and full-face settings. The air rush noise was also confirmed by Satar *et al.* (2019a), wherein the measurement was conducted in several HVAC components such as compressor, air conditional (AC) pipe, evaporator, and thermal expansion valve (TVX). The noise was heard within the frequency range of 1400–1700 Hz. In another study by Satar *et al.* (2019b), the authors found the humming noise in the frequency range of 300–350 Hz and 150–250 Hz for the ambient and operating conditions, respectively. The sources of the noise were the compressor, AC pipe, and power steering pump for both conditions. The authors also proposed the existence of clicking noise as an effect of the engagement impact of the magnetic compressor clutch. The component that contributed the most was the compressor, which was found at frequency range of 200–300 Hz.

Thawani *et al.* (2013) proposed the gurgling noise in the mechanism of refrigerant flow. This noise is generated when the refrigerant (i.e. R134a) with high pressure and temperature is forced to flow through a small passage of orifice. In an abnormal instance, when the vehicle is running more than 5 hours and the AC is turned on suddenly, the gurgling noise can be generated. The authors also highlighted the presence of noise in the operating frequency range of 2000–10 000 Hz. Meanwhile, Paiman *et al.* (2018) expanded the work in different HVAC noise types and successfully found the hissing noise within the operating frequency of 4500–5000 Hz for both idle and running conditions, and the highest contributor for this noise was evaporator. An incremental and continuous evaluation of the works was conducted by authors in the area of vehicular noise characterization. It should be noted that the scope of those studies was within a limited frequency range and limited measurement of the contributing components. Also, the research studies did not attempt to relate the vibration contribution from another component to the generation of hissing noises.

An evaluation of the vibration and noise contribution by the computational fluid dynamics (CFD) method has been an attractive option for the last two decades. Patidar *et al.* (2009) evaluated the HVAC performances using different parameters: pressure drop in the system, airflows at the outlets, and discharge in interior space. Our work visualizes the velocity and pressure changes over the face with defroster, and foot modes implemented in the HVAC system. Since the blower is a crucial component of noise generation, Jäger *et al.* (2008) simulated the noise generated by a flap in a simplified duct. The findings agreed with Gren *et al.* (2012) and Pérot *et al.* (2013), wherein both the researchers were also able to prove noise propagation in the near field downstream and verified with the experimental work. Toksoy *et al.* (1995) proposed a new design of the blower wheel and investigated the different parameters that contributed to the noise levels and inferred that it was possible to improve the overall efficiency by improving flow performance and reducing the noise. Sah *et al.* (2013) expanded the investigation on fans, duct flaps and plenum volume discharge. The flows were simulated from the noise origin, which was near the field downstream of the HVAC system in combination with the ducting system. However, the computational time required to simulate the model was too long (337.5 hours). Mann *et al.* (2015) developed a numerical method to simulate and improve the design of the mixing unit with a blower and was able to reduce the level of noise by 4.5 dBA.

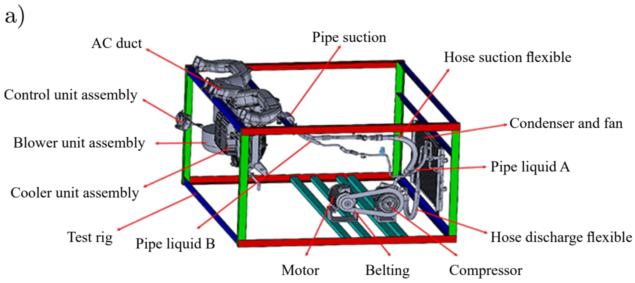
Although there are extensive studies involving CFD method, they are only limited to thermal and airflow characteristics with limited components (Fischer, 1995; Kwon *et al.*, 2015). Comparatively, lab-scale systems offered a detailed understanding with lower time consumption, particularly involving the investigation of reverberation in the vehicle cabin area, in which the CFD method has a higher computational time (Sah *et al.*, 2013). It is important to study the characteristics of noise in a real-time application since acoustics cannot be accurately characterized in other modes of analysis. Wang *et al.* (2018) stated that acoustic felt was perceptive and more effective in a real application. The noise type, for instance, hissing noise, needs a real application to be studied for their characteristics. The advantages and limitations of different models motivated this study to further investigate the noise characteristics by developing a lab-scale HVAC system that was able to reflect the real operations. All the components were assembled, and the measurements were conducted in the laboratory, which provided more reliable results. The verification of the results was then carried out in a real vehicle. With the lab-scale system developed, the study is aimed to provide better understanding of the vibration generated in all the components of the HVAC system. The related attributes of the components with the hissing noise is the focus of this study. Different engine speeds were set to allow variation of the frequency range, wherein the hissing noise is produced.

2. Methodology

2.1. Design and implementation of lab-scale HVAC system

Figure 1a shows the 3D CAD design of the proposed lab-scale HVAC system developed using SolidWorks software. A complete view of the assembly that comprises of all the HVAC components used for the experimental investigation is shown in Fig. 1b.

a)



b)

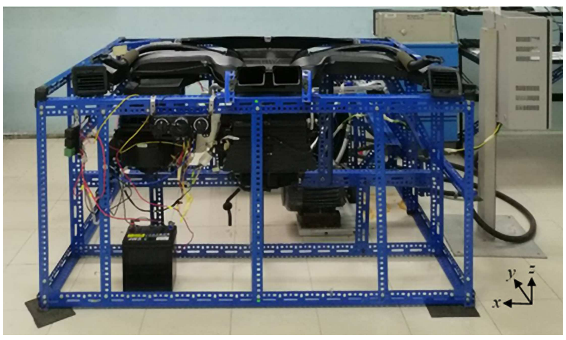


Fig. 1. (a) 3D CAD design of the lab-scale HVAC system ad (b) actual implementation of the HVAC system.

The components were fastened firmly to a test rig. A motor was used to drive the compressor through a belt-drive powered by a 12 V battery. The mechanism of the lab-scale system was monitored as soon as it was started. As air enters the evaporator and passes this component, the coils absorbs the heat and gets converted into low-pressure vapour. The low-pressure vapour is then converted to superheated vapour. Subsequently, it flows through the condenser, where the refrigerant is condensed and releases heat to become liquid but still maintained at high-pressure. The heat release is also contributed by the radiator as the heat gets blown out from the system. Again, the liquid flows to the expansion valve, which allows the pressure of the liquid to be reduced to lower levels. This low-pressure liquid flows to the blower and dissipates to the vehicle interior space, as cool or warm conditioned air. The above process is repeated to form one complete cycle (Jabardo *et al.*, 2002; Daly, 2006; Okuma *et al.*, 2012).

2.2. Stages of noise and vibration measurement

2.2.1. Stage 1: Problem identification

The study begins with the identification of the main problems related to the occurrence of vibration and hissing noise in the lab-scale HVAC system. The hissing noise was characterized by a soft and low pitch sound. This noise was also generated at high frequency range, as suggested by Soeta and Shimokura (2017). It emanated from the HVAC system components which were based on the interrelated vibration elements. The vibration caused the generation of noise with different characteristics.

2.2.2. Stage 2: Measurement

After identifying the problems, the measurements were carried out using different types of sensors (tachometer, accelerometer and microphone), and subsequently, the evaluation of the vibration and noise characteristics were performed for the recorded data. The sound diagnosis method was employed to verify the correlation between the vibration response and hissing noise.

2.2.3. Stage 3: Validation

In this stage, the data obtained were validated with the vehicle system, wherein the reliability of the analysis using the model is ascertained, and the exact locations of the noise sources can also be determined.

2.3. Experimental set up

In this study, the engine speed was measured by a tachometer (Monarch, type: SPSR-115/300) that was mounted on the compressor. The engine speed was maintained at 850 rpm and between 850–1400 rpm for the ambient and operating conditions, respectively. A foot pedal was used to conveniently control the speed in the vehicle system. The vibration response was measured by the miniature accelerometers (Kistler, type: 8776A50), which were mounted on the HVAC components. For both lab-scale and vehicle HVAC systems, a total of five suspected components were considered that might be subjected to the vibration in the system. The suspected components were the compressor, motor, TVX, evaporator, and AC pipe. Figures 2 and 3 show the images of the accelerometer attachment for the lab-scale and vehicle systems, respectively. The HVAC components were considered based on the contributions estimation as described by Thawani *et al.* (2013).

a) b) c)

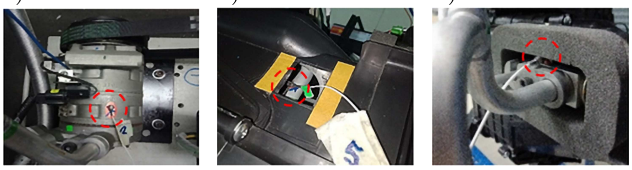


Fig. 2. Accelerometer placement on the: a) compressor, b) evaporator, c) TVX of the lab-scale HVAC system.

a) b) c)

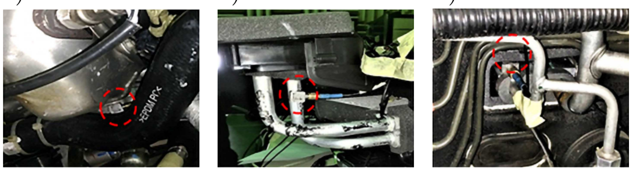


Fig. 3. Accelerometer placement on the: a) compressor, b) evaporator, c) TVX of the vehicle HVAC system.

The noise measurement was carried out using a microphone (BSWA, type: MA231). The microphone was placed at a distance of 10 cm from the HVAC components with an offset of 10 cm, as experimented by Putner *et al.* (2013). For the vehicle system in Fig. 4, one microphone was placed at the center outlet to confirm the existence of the hissing noise and this location was the source of noise generation into the interior cabin area. The microphone sensor was connected to data acquisition, namely as LMS SCADAS Mobile. The software used for processing the obtained data was LMS Test. Xpress and LMS Test Lab Acoustics. In this analysis, a frequency range below 10 000 Hz was selected since it is the audible range, as studied by Gren *et al.* (2012) and Sah *et al.* (2013).

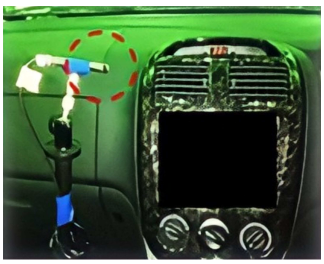


Fig. 4. Microphone arrangement at the center outlet of the vehicle HVAC system.

3. Results and discussions

3.1. Ambient condition

3.1.1. Vibration frequency response

Figure 5 shows the vibration frequency response of the major components that contributed to the hissing noise of the lab-scale HVAC system. Out of the five components, motor produces the most significant vibration, which is up to 0.0052 m/s^2 in the operating frequency of 3500–4000 Hz. During the ambient condition of 850 rpm, the rotation of motor was rough and produced a quite significant noise. However, this is not indicated as hissing noise since the peaks were dominant at different frequency range (Rahman *et al.*, 2018). A following major contribution was the evaporator with 0.0035 m/s^2 of vibration amplitude in the operating frequency range of 5000–6000 Hz. The compressor, AC pipe and TVX were another moderate contribution to the noise generated. Even though the vibration and noise are interrelated, on verification of all the five components, motor, compressor and AC pipe were not responsible for the generation of the hissing noise. The verification indicates that the evaporator and TVX were the main contributors even though the vibration response was relatively lower compared to motor. After conducting a series of processes for identifying the frequency range of the hissing noise, a frequency range of 4000–6000 Hz was traced as the active range of the generated noise. This frequency range will be verified with the hissing noise measurement results in the next section.

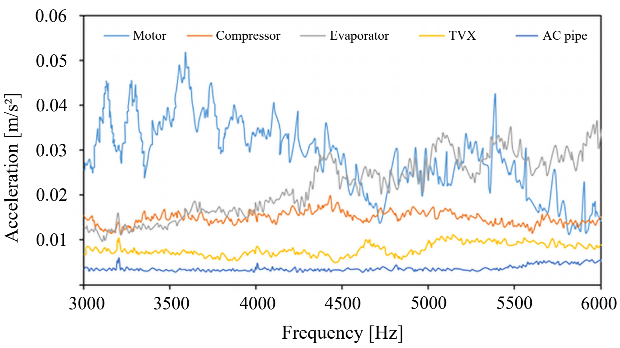


Fig. 5. Vibration frequency response of five main components of the lab-scale HVAC system (ambient condition).

The vibration frequency response obtained during the validation process with the vehicle HVAC system is presented in Fig. 6. The two components, namely evaporator and TVX, showed domination vibration within the frequency range of 4500–5500 Hz, wherein

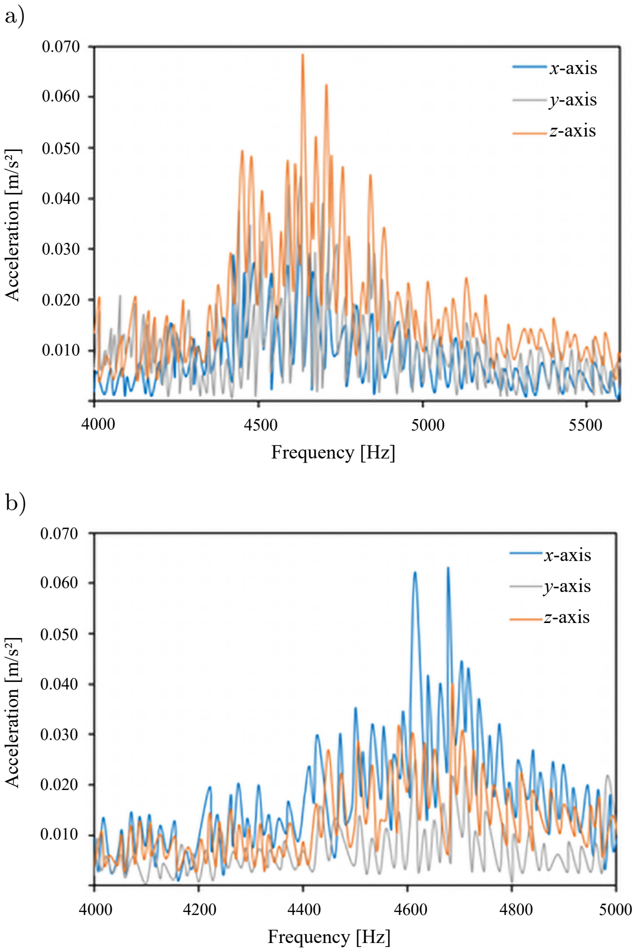


Fig. 6. Vibration frequency response of (a) evaporator and (b) TVX of the vehicle HVAC system (ambient condition).

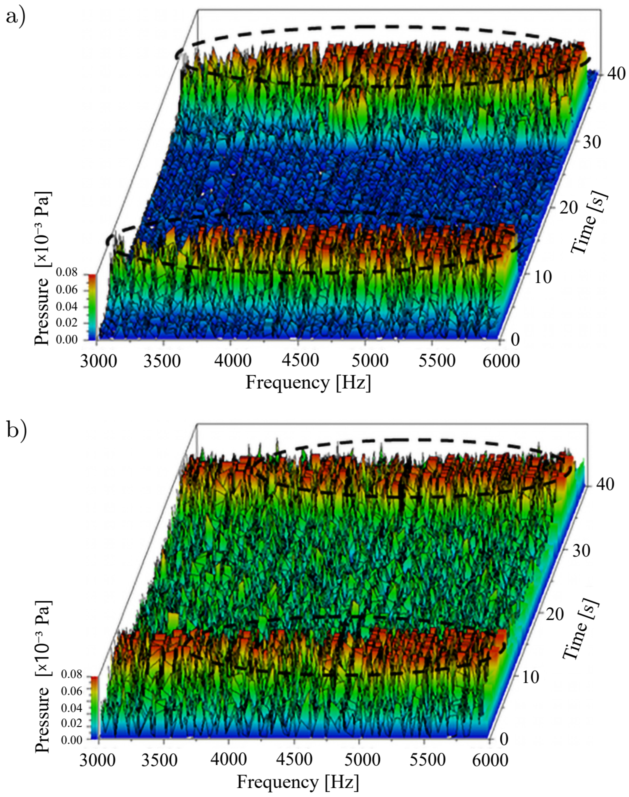


Fig. 7. 3D noise waterfall for (a) evaporator and (b) TVX of the lab-scale HVAC system (ambient condition).

the highest amplitude for the evaporator and TVX were recorded at $0.07\ \text{m/s}^2$ (z-axis) and $0.013\ \text{m/s}^2$ (x-axis), respectively. The other axes moderately affected the noise generation. In overall, the results were in good agreement with the lab-scale HVAC system as the same sources (evaporator and TVX) were observed to contribute to the hissing noise. The figures also show the respective axis components that have a significant contribution to the hissing noise in detail.

3.1.2. 3D noise waterfall

The 3D noise waterfall plot provides the details of the HVAC noise response with respect to the frequency and time (Braun *et al.*, 2013). Figures 7a and 7b show the 3D noise waterfall that was recorded for the evaporator and TVX of the lab-scale HVAC system, respectively. From the figures, significant peaks with high noise amplitudes within the frequency range of 4000–6000 Hz can be observed to occur periodically, from 0–10 s and 30–40 s (i.e. during the compressor engagement). The sound pressure level (SPL) of these compressor engagement periods reached up to $0.08 \cdot 10^{-3}$ Pa (A) for almost every crest.

In order to validate the source of noise as represented in the lab-scale HVAC waterfall diagram in Fig. 7, the noise measurement in the interior space of the vehicle was carried out at the center outlet, and the finding is presented in Fig. 8. From the figure, it can be observed that there is a high intensity of SPL, ranging between 4500–5500 Hz. This is comparable with the lab-scale HVAC findings in Fig. 7, whereby the results of sound diagnosis also indicated that the ge-

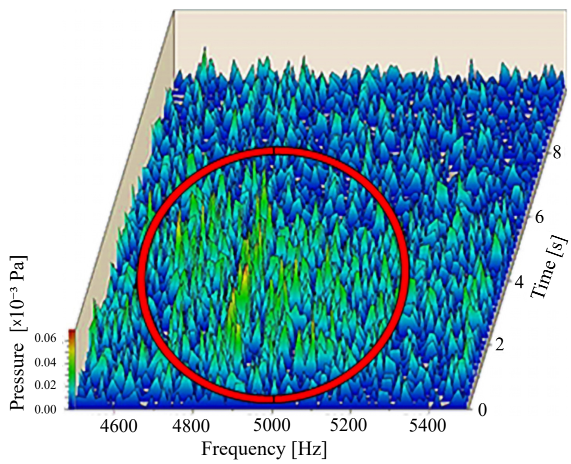


Fig. 8. 3D noise waterfall at center outlet of the vehicle HVAC system (ambient condition).

neration of hissing noise was dominated between the similar frequency ranges.

As shown in Fig. 7 previously, the periodic occurrence can be represented by the engaging action of the compressor clutch in time domain, as depicted in Fig. 9. The vibration response was consistently higher and lower during the compressor engagement and disengagement in a periodic manner. Figure 9 shows that the higher vibration responses of the engagement for the compressor and evaporator were up to 13 m/s^2 and 0.9 m/s^2, respectively. However, during the disengagement period, the vibration amplitude was reduced to 2 m/s^2 and 0.313 m/s^2 for the compressor and evaporator, respectively. The detailed observations indicated that the hissing noise was generated as a result of the expansion process of the refrigerant at an interface between the high and lower pressure side of the vehicle HVAC system. The expansion process can be represented by TVX, however, a remarkable vibration only occurred at the evaporator pipe inlet that spread up until the evaporator core, which subsequently caused the noise to be audible inside the vehicle cabin. In addition, the presence of the hissing noise was evident only after a few seconds of initiation of the compressor magnetic clutch during engagement. It lasted for 6 s before the clutch was detached. The measurement that had been carried out had the notable consensus with the driver and passengers experience while seated inside the cabin, as interpreted previously in Fig. 8.

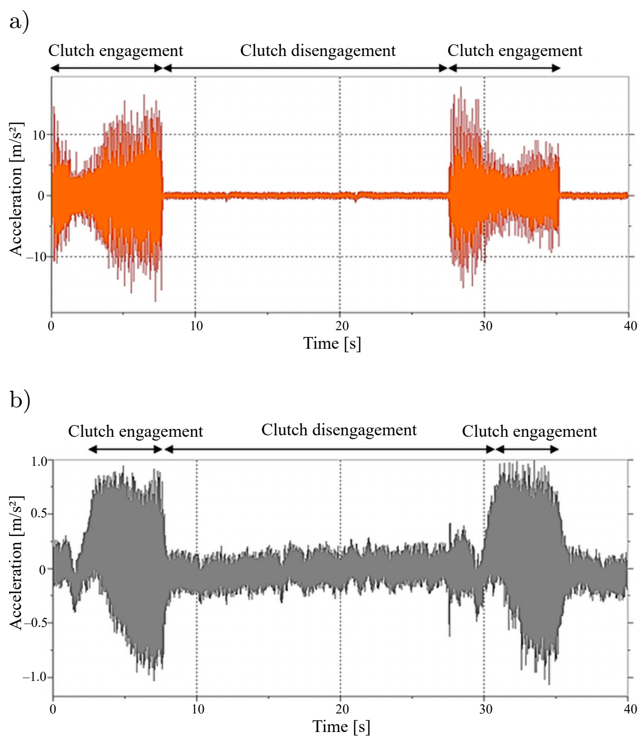


Fig. 9. Real-time vibration response of (a) compressor and (b) evaporator during the ambient condition.

3.2. Operating condition

3.2.1. Vibration frequency response

Figure 10 shows the vibration frequency response from the five main components of the lab-scale HVAC system in operating condition. The hints from audio verification in previous section indicated that the frequency range of interest was between 4000–6000 Hz for the hissing noise generation. From Fig. 10, the observation shows that the evaporator dominates the vibration peak amplitude approaching 0.015 m/s^2 at 4500 Hz. The higher vibration trend was also observed for the compressor with 0.009 m/s^2, while the motor and AC pipe only contributed to a smaller extent. Although the TVX contributes moderately to the total vibration, the audio verification indicated that the hissing noise was primarily imparted by the evaporator and TVX. This can be verified by the result of hissing noise measurement in the next section.

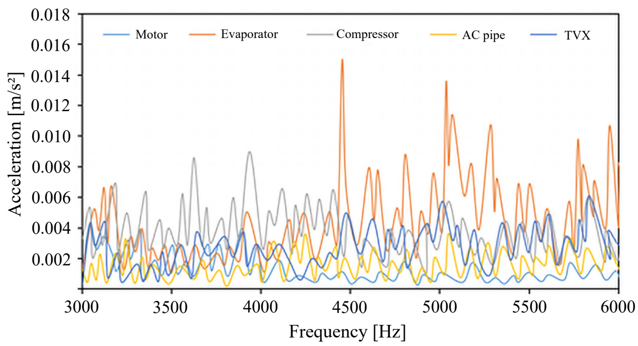


Fig. 10. Vibration frequency response of five main components of the lab-scale HVAC system (operating condition).

A similar observation can be made for the vehicle HVAC system, wherein the results of vibration frequency response for the evaporator and TVX that contribute to hissing noise production are shown in Figs 11a and 11b. The figures shows that the evaporator and TVX produced the vibration with the amplitude of 0.06 m/s^2 and 0.015 m/s^2 dominantly in the z- and x-axes, respectively, while other axes slightly contributed to the noise. It was also noticed that the responses obtained were similar to the lab-scale HVAC system that ranged from 4500–5500 Hz, the frequency range at which hissing noise was heard.

3.2.2. 3D noise waterfall

In this section, the noise response for increasing motor speeds from 850–1400 rpm was analyzed using the 3D waterfall plot. Figures 12a and 12b show the 3D waterfall plot of the suspected components (evaporator and TVX) involved in the contribution of the hissing noise at the lab-scale HVAC system. Figure 12 shows the hissing noise for both evaporator and TVX which can be clearly observed during tracking rpm

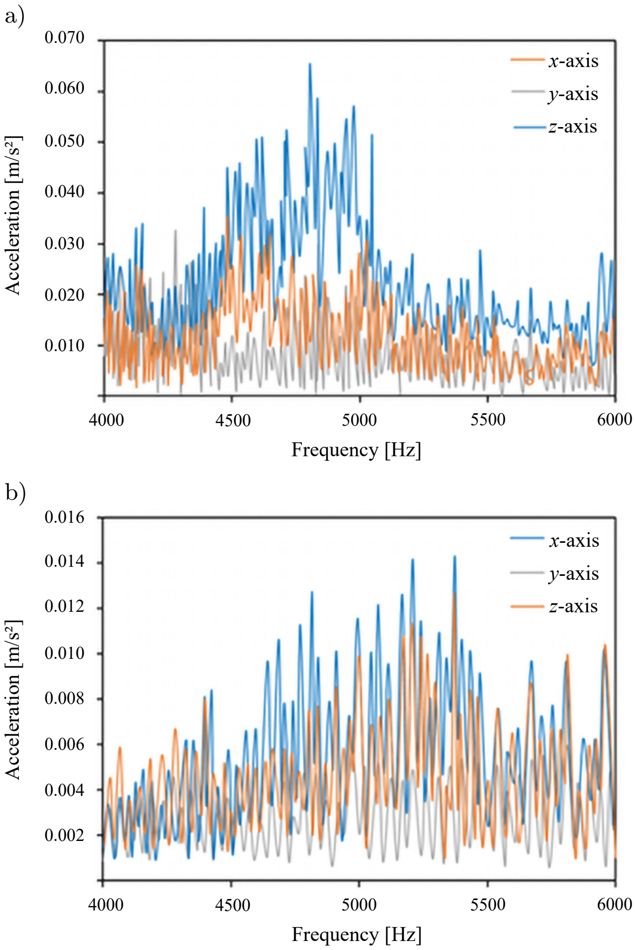


Fig. 11. Vibration frequency response of (a) evaporator and (b) TVX of the vehicle HVAC system (operating condition).

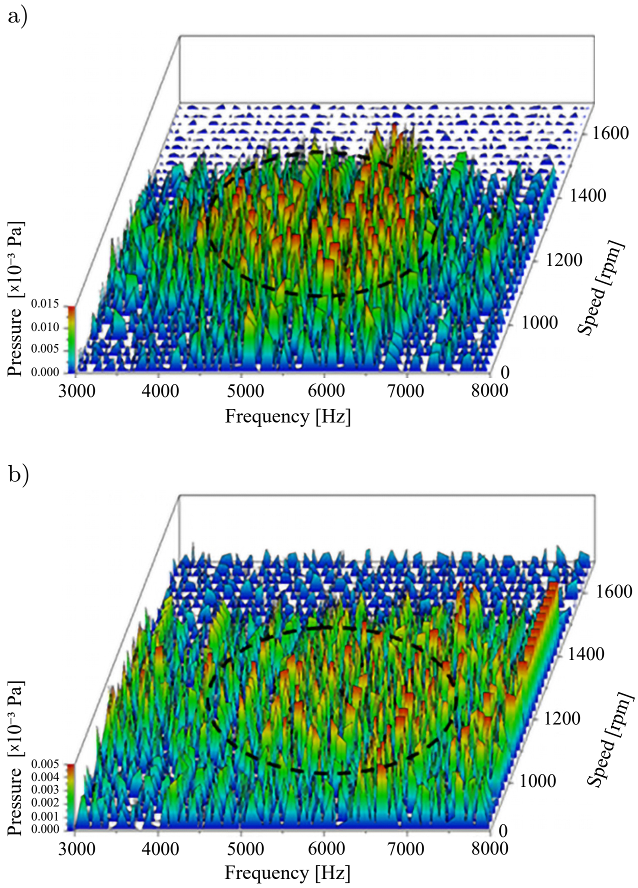


Fig. 12. 3D noise waterfall for (a) evaporator and (b) TVX of the lab-scale HVAC system (operating condition).

from 850–1400 rpm, wherein there are high noise amplitude scattered between 4000–7000 rpm. This noise concentrated in the middle region also produced the SPL value up to $0.015 \cdot 10^{-3}$ Pa (A). This may be explained by the HVAC effect pattern, which determined whether the refrigerant used was circulating in the system. Since the compressor worked to compress the refrigerant, this component relates to the data obtained in Fig. 9. It is understood that the clutch engagement process allowed the circulation of the refrigerant in the HVAC system by engaging both of its rotating pullets and the pulley, and this process leads to the high amplitude of vibration. On the other hand, during the clutch disengagement process, the refrigerant flow is restricted, and yet a significant amplitude of vibration can be observed as shown previously in Fig. 9 (Terauchi *et al.*, 2018).

Based on this analysis, the hissing noise was also validated at the center outlet location of the vehicle interior, which is presented in Fig. 13. The figure indicates that there is a high colour intensity that concentrates between the ranges of 4800 to 5300 Hz during operation condition. The SPL at the center outlet

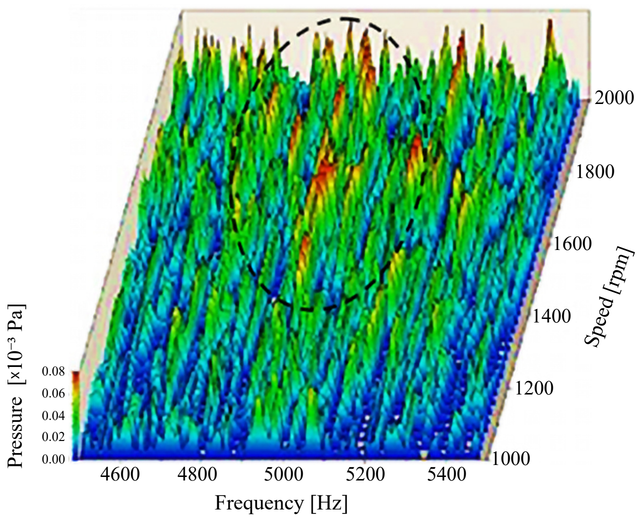


Fig. 13. 3D noise waterfall at center outlet of the vehicle HVAC system (operating condition).

reach up $0.08 \cdot 10^{-3}$ Pa, which indicates the presence of hissing noise. The sound diagnosis found that the noise presence in this range was louder compared to that of the ambient condition as the noise tends to amplify as the engine speed increases. However, there was no specific value of rotational speed, wherein the vibration and noise created are critical.

3.3. Vibration and noise coherences

In this section, the hissing noise and vibration data coherences are presented and verified for two major HVAC components during the operating condition. Figures 14a and 14b show the comparison between the vibration and noise data induced by the evaporator and TVX, respectively. As shown in Fig. 14a, there are high vibration and noise amplitude trends within the frequency range of 4000–6000 Hz for the evaporator, whereby the amplitude for both vibration and noise started to increase in this region, which indicates the existing of hissing effect. Figure 14b highlights it more clearly for the TVX component, whereby the hissing noise and vibration data trends are almost identical within 4000–6000 Hz of frequency range. As verified using sound diagnosis, both HVAC component noises are confirmed to be a hissing type of noise as discussed by Rahman *et al.* (2018) and Satar *et al.* (2019a).

a)

b)

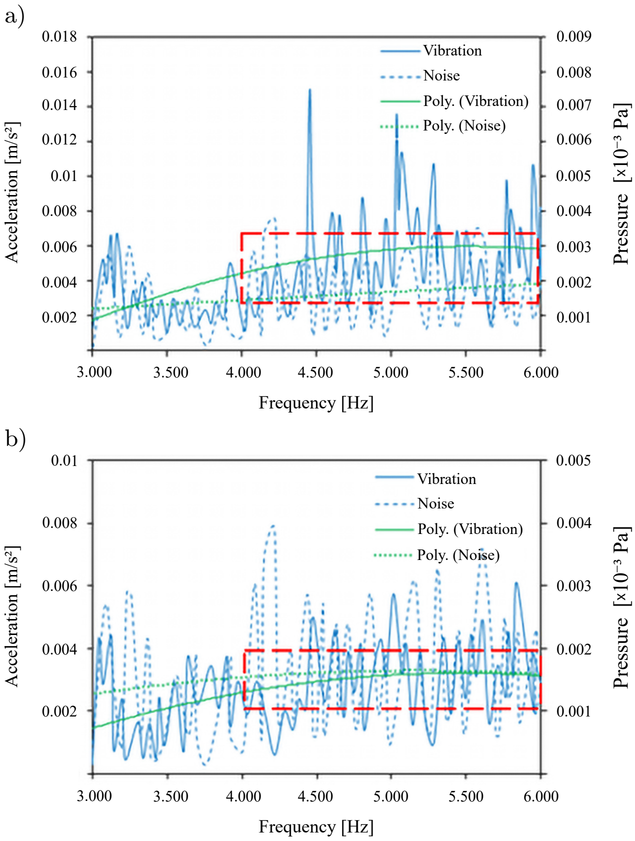


Fig. 14. Vibration and noise coherences of (a) evaporator and (b) TVX during operating conditions.

4. Conclusion

In this study, a lab-scale HVAC system was developed to characterize the hissing-type of noise and vibration and validated with the vehicle system. Two major HVAC components which are evaporator and TVX were identified as the sources that contribute significantly to the hissing noise. The detailed evaluation of the sources confirmed that the hissing noise of contributing components originated from the compressor. The results also highlighted that the noise occurred periodically due to clutch engagement and disengagement processes, and the operating condition witnessed a louder noise compared to ambient condition. A remarkable agreement of the findings between lab-scale and vehicle HVAC systems for both the conditions was observed, wherein the hissing noise was evident in the frequency range of 4000–6000 Hz.

Acknowledgement

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