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Characterisation of the Humming-Type Noise and Vibration of the Automotive HVAC System

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ABSTRACT

The automotive heating and ventilating air condition (HVAC) system, when vibrating, can generate various types of noises such as humming, hissing, clicking and air-rushes. These noises can be characterized to determine their root causes. In this study, the humming-type noise is taken into consideration whereby the noise and vibration characteristics are measured from various HVAC components such as power steering pump, compressor and air conditional pipe. Four types of measurement sensors were used in this study - tachometer for rpm tracking; accelerometer for the vibration microphone for the noise; and sound camera for the visualization measurement. Two types of operating conditions were taken into consideration - they were "idle" (850 rpm) and "running" (850-1400 rpm) conditions. A constant blower speed was applied for both conditions. The result shows that the humming noises can be determined at the frequency range of 300-350 Hz and 150-250 Hz for both idle and running conditions, respectively. The vibration of the power steering pump shows the worst acceleration of 1.8 m/s^2 at the frequency range of 150-250 Hz, compared to the compressor and air conditional pipe. This result was validated with the 3D colour order and sound camera analyses, in which the humming noise colour mapping shows dominance in this frequency range.

Keywords: Humming noise; HVAC system; vibration; rpm tracking; power steering pump.

INTRODUCTION

Comfort is a key factor for most of customers in purchasing a vehicle. The comfort of the driver and passengers extends to the noise that they are subjected to, including the noises that are induced from the heating and ventilating air conditional (HVAC) system [1, 2]. Responsible for the heating, cooling, circulating and purifying the air in the cabin, the HVAC system has a large impact on the well-being of the occupants of the vehicle, since it can be a significant noise and vibration sources to the vehicle cabin. A typical HVAC system consists of several assembly parts such as compressor, condenser, radiator fan, drier, thermal expansion valve (TXV), evaporator and blower [3, 4], as shown in Figure 1 [4]. In an operating condition, the compressor is exacted to compress the air in high pressure condition. The increase of temperature causes the air to be converted to a liquid state, which then go through the condenser and radiator fan of the HVAC system with the released of heat. This high-pressure liquid flows towards the drier and TXV, whereby at this component the high-pressure liquid is converted into low-pressure liquid. The low-pressure liquid further flows into the evaporator and blower which then convert it into low-pressure air, to be spread inside the vehicle cabin as cool or warm conditioned air [5]. This sequence is repeated consistently for the constant air-flow setting and may vary if the speed of air-flow is changed [6].

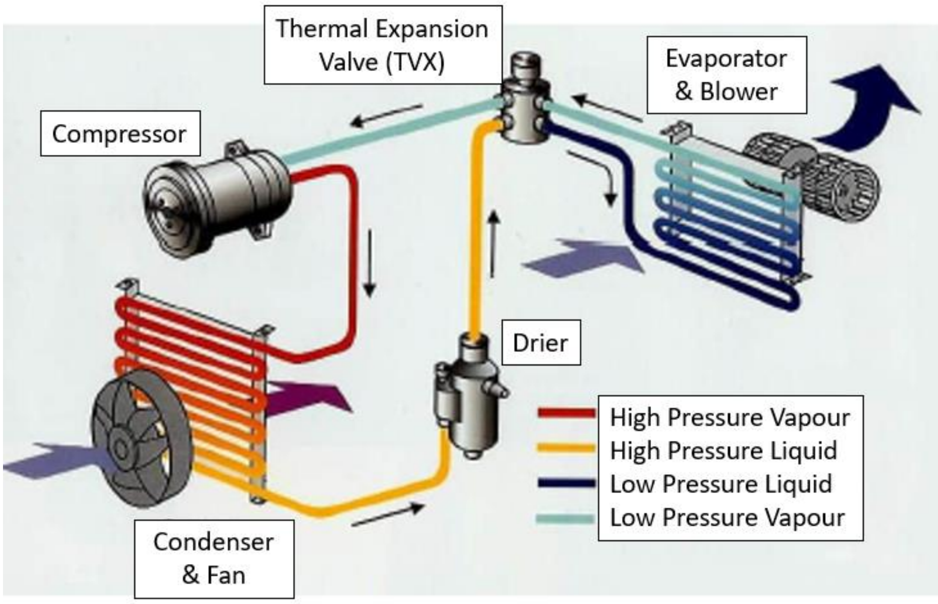


Figure 1. Common vehicle HVAC system.

For many automotive manufacturers, the noises emanating from the HVAC system is a common problem. Several types of noises can be produced by an HVAC system, such as buzzling, hissing, humming, air rush, knocking. These noises can pose a significant issue to driving comfort. For example, the buzzling noise from the compressor while the air conditioning is turn on is due to the liquid refrigerant flow to the compressor, and this is a sign of the system being overcharged [7]. This is the most common noise problem to the HVAC system which can damage the compressor part if no necessary action is taken. The compressor part basically has the highest sound pressure level (SPL) and it increases with time due to the wearing-off of the vibration pad to mount the compressor to the metal casing. In this case, nothing much can be done since the internal mechanical parts are inaccessible, unless permitted by a design change of the compressor part [8].

Another example of noise problem of the HVAC system is a knocking noise. This noise is produced by the loose mounting bolts of each part in the HVAC system [7]. The loose mounting bolt will generate an unwanted vibration phenomenon to the HVAC system which subsequently induced the knocking noise. Even though this is a rare noise problem of the HVAC system, it must be solved before any unwanted system failure happens.

Vibration is a motion with periodic oscillation occurred from its equilibrium point [9]. This characteristic has gained considerable attention from diverse field of researchers since it has potential harm that can affect the performance of the system. The studies on human arm [10], building structure [11] and scanning probe [12] are examples involving vibration. Specifically, it has also been covered in the study of its effects on automotive, but the characterizations in HVAC system has not been well considered. The HVAC system component is a crucial section to be focused on since it contributes to major vibrations and noises in a vehicle's interior space [13]. The blower is a critical part of the HVAC system since it is mounted inside the cabin of the vehicle and is a major noise source in this system [13–17]. For example, the noise flow induced by the rotation of HVAC blower is shown in Figure 2 [21]. This phenomenon occurs due to the rotating and turbulent air flow of the unit through the ducting and ventilation outlet. The turning location near both outlets causes a turbulence flow and generates more noises [18]. In order to reduce the effects of HVAC noises, the solution can be carried out in terms of passive or active noise [13, 16, 17] and vibration controls [19, 20]

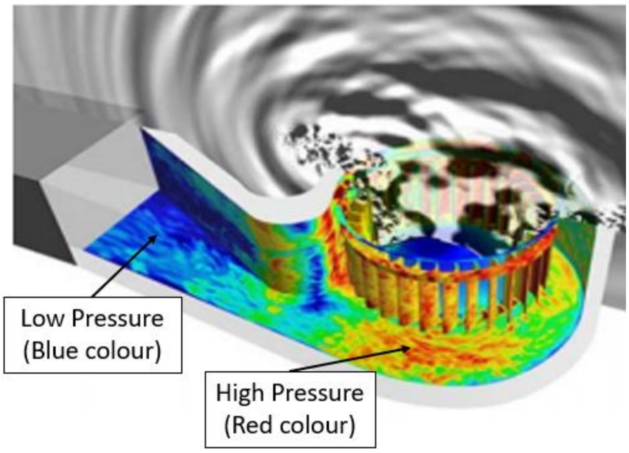


Figure 2. Noise flow induced by the rotation of HVAC blower.

To determine the root cause and type of noise and vibration of the HVAC system, a proper setup and measurement strategy must be carried out. The study done by Mavuri, et al. [22] shows the proper methodology in measuring the vehicle HVAC cabin noise such as the instrumentations to be used, testing parameters involved and the setup procedures. The noise of the HVAC system is measured in four conditions:1) in neutral condition with HVAC off; 2) in neutral condition with HVAC working in Full Face-Full-Cold-Re-Circulation (FFRC) mode; 3) in driving condition with HVAC off; and 4) in driving condition with HVAC working in FFRC mode.

In another study, the lab scale rig had been setup to determine the noise created from the air handling unit of the HVAC system [23]. In this experiment, the fan speed of the HAVC system was set as 1880 rpm, 2120 rpm, 2360 rpm and 2600 rpm with the blade passing frequency (BPF) from 1410 to 1950 Hz. The result shows that, the increasing of the fan speed increases the BPF and contributes to the increment of the total noise level and magnitude of the predominant noise spectral peaks. In addition, the implementation of motor vent hole cover does not affect the total noise level but reduces the noise spectral peaks at the BPF and cavity resonance peaks at low frequencies.

As it is well-known that there are various types of noises that can be induced from the HVAC system, this study only focuses on one of the most critical types of noise which is the humming-type noise that is generated from several vehicle HVAC components. This noise occurs due to the high rotational speed of the fans [24], its low structure integrity [25] and its vibration [26]. And may lead to future risks such as increase stress level [27] and heart- rate [28] of occupant. In this study, it consists of in-vehicle vibration and noise measurements at related HVAC components such as power steering pump, compressor and air conditional pipe to determine which components caused the humming-type noise problem.

METHODOLOGY

Flow Chart of Noise and Vibration Measurement

In this section, the overall flow chart of the study is shown in Figure 3. From the figure, the study started out with subjective feeling in identifying the noises that were emanating from the HVAC system which were considered as problems. Once the problem noises have been identified, some hypothesis was done to determine the suspected noise sources from the HVAC components. From here, the required sensors such as accelerometer, microphone, tachometer and sound camera mounting locations were decided for the data measurement process. The frequency content data was recorded for the noise and vibration analysis and then verified using the visual data from the sound camera and noise filtering using the sound diagnosis method. After the verification, the conclusion on the type of noise and root cause location was made. This process is important for automotive manufacturers to determine the exact location of the HVAC noise and vibration problem and come up with the solution.

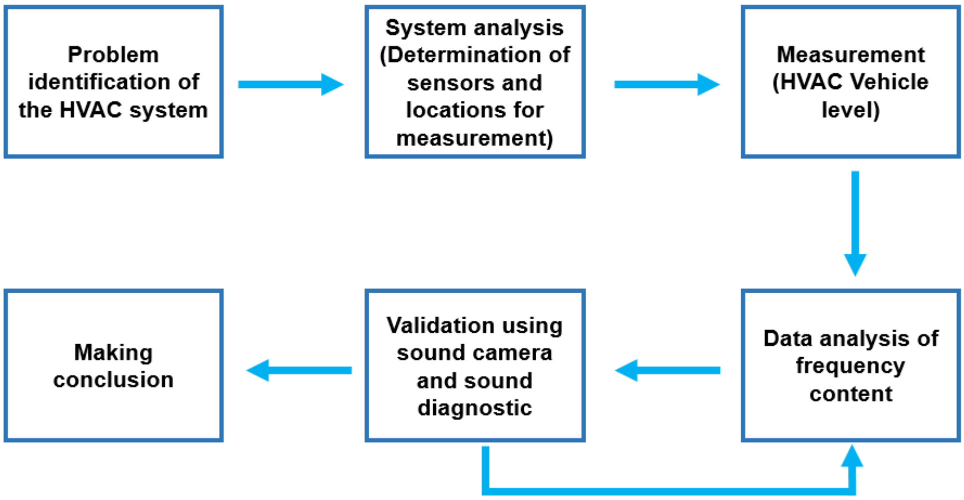


Figure 3. Methodology flow chart.

Experimental Setup

In this section, the experimental setup for the in-vehicle vibration and noise measurement are explained. Figure 4 (a) and (b) show the test flow chart and test locations of the vehicle HVAC system vibration and noise measurement. As shown in Figure 4(a), there are four types of sensors being used. They are tri-axial accelerometer (x, y and z directions) for the vibration measurement; microphone for the noise measurement; tachometer for the rpm tracking measurement; and finally, the data is verified using the sound camera for noise visualization measurement. The tachometer is mounted at the rotating engine belt to measure engine rotating rpm during idle, and also to measure the engine rpm tracking conditions. Three accelerometers are used and mounted by wax on the air conditional pipe, power steering pump and compressor locations.

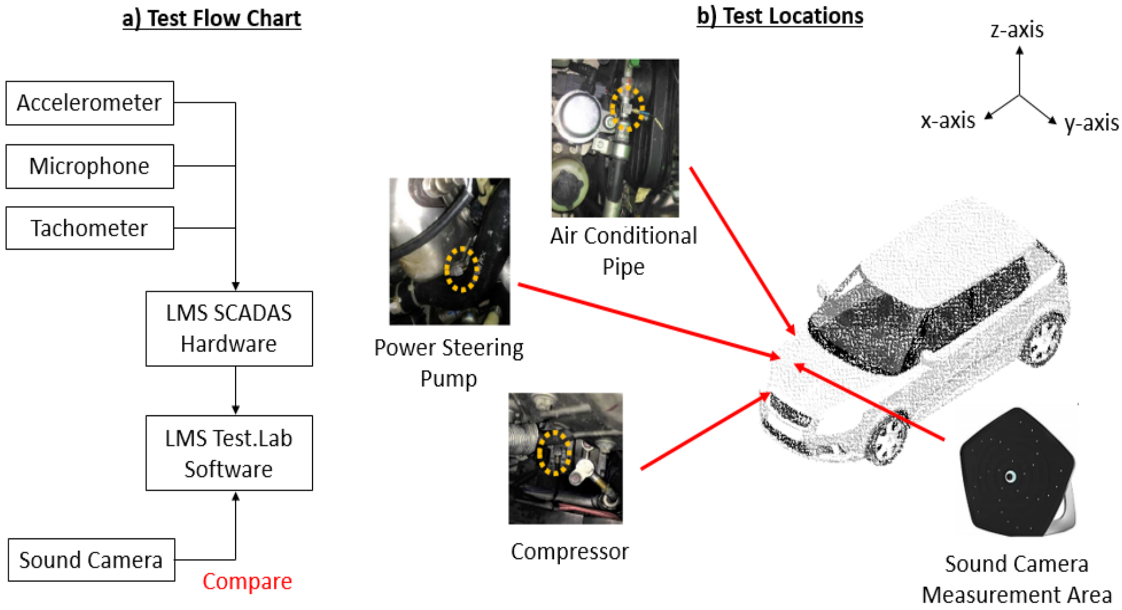


Figure 4. (a) Test flow chart and (b) Test locations of the vehicle HVAC system.

Figure 5(a) to 5(c) show the tri-axial direction applied in this experimental set up. Importantly, these three components are suspected to be the major contributors to the humming-type noise that had affected the subjective feeling during the problem identification stage. A microphone is mounted at the compressor area to collect data, and this data is then used to verify the noise from the measured vibration response. The exact sensors mounting locations for the vibration and noise measurement are shown in Figure 4(b).

The signals from accelerometer, tachometer and microphone sensors are recorded using LMS SCADAS Mobile (64 channels) hardware that integrates with the LMS Test.Xpress (frequency spectrum). This software records the time and frequency domain data from these sensors and transfer them to the LMS Test.Lab software for further analysis. Using the LMS Test.Lab software, the raw data of the frequency content from LMS Test.Xpress can be analysed, and the specific vibration and noise figures can be generated. The detailed analysis using Sound Diagnosis workbench is then carried out with its filtering function in order to extract an actual humming-type noise characteristic.

After the extraction of humming-type noise using the Sound Diagnosis, the data is then verified using the Sound Camera that are mounted above the engine bay area as shown in Figure 4(b). The frequency range of humming-type noise can be captured using the Sound Camera and then compared with the Sound Diagnosis by hearing and visualization.

Condition of Noise and Vibration Measurement

Table 1 shows the testing conditions for the vibration, noise and rpm tracking measurement of the vehicle HVAC system. There are two test conditions applied in this study, which is in idle condition (engine speed maintain at 850 rpm) and in rpm tracking condition (engine speed increasing from 850 to 1400 rpm). The idle condition refers to the vehicle’s engine running but not in motion, used in this study as a reference condition. While the engine is in motion, the engine speed range from 850 to 1400 rpm is selected -

this condition theoretically has more noise and vibration produced, since it involves more operations in the HVAC. In this experiment set up, only one air conditional status is used (i.e. "on" status) in the idle condition, and the blower speed is set to the speed of 0.25. Since this is an initial investigation to determine the root cause of the humming-type noise, only one level of blower speed (i.e. 0.25 speed) is considered. Further investigation for various blower speed settings can be done after determining the root cause of the noise. For the second case of engine in rpm tracking condition, two air conditioning status are applied (i.e. "on" and "off" status), so that the effect of air conditioning can be determined. The speed of the blower for this case is set to 0.25 as in idle condition.

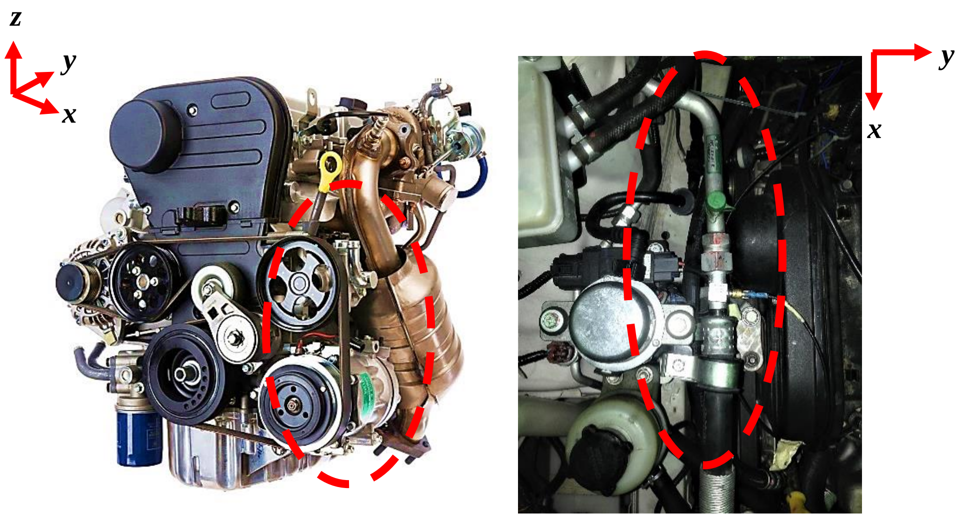


Figure 5. Components assemble position and arrangement. (a) Compressor and power steering pump driven by same belt. (b) AC pipe with mounting attached on vehicle structure.

Table 1. Testing condition of the HVAC system.

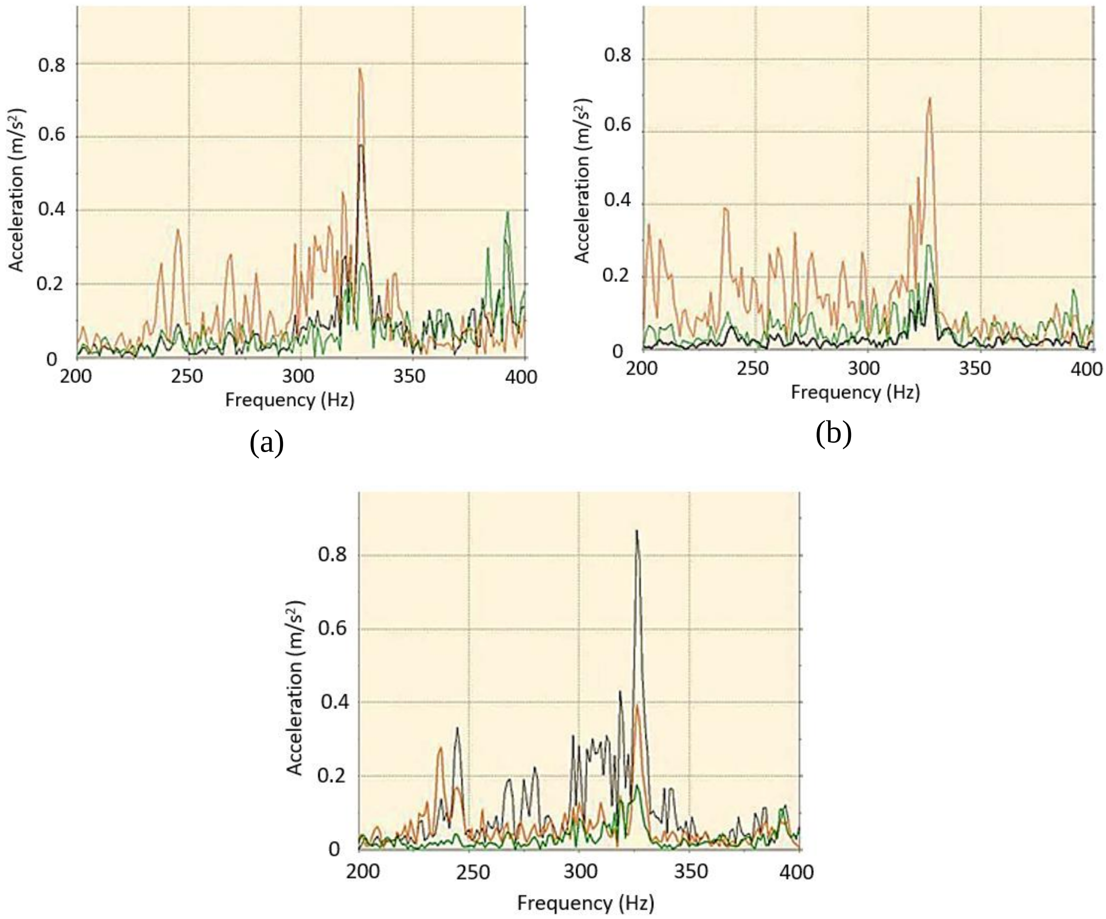
Type of noise	Test conditions	Engine status	Air conditional (AC) status	Blower speed	Locations
Humming	Idle (850 rpm)	On	On	0.25	- Power steering pump - Compressor - AC pipe
	rpm tracking (850-1400 rpm)	On	Off	-	
		On	On	0.25	

RESULTS AND DISCUSSION

Frequency Domain Analysis

Idle condition

In this section, the result of humming-type noise in terms of vibration amplitudes are presented using the frequency domain method. Figure 6(a) to (c) shows the vibration response in *x*, *y* and *z* direction at compressor, power steering pump and AC pipe. The maximum response occurs between frequency ranges of 300 to 350 Hz for each component. The highest vibration is produced by the AC pipe, which approaches 9 ms^{-2} in *x* direction, while the vibration produced for power steering pump and compressor is approximately 7 ms^{-2} and 8 ms^{-2} respectively. Both highest responses are recorded in *y* direction. The justification and verification of the frequency domain analysis are explained further in sound camera verification section.

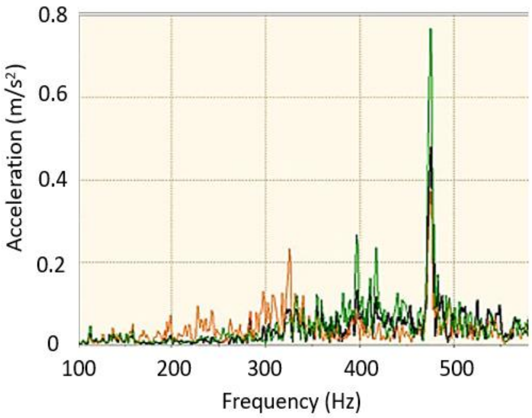


(a) (b) (c)

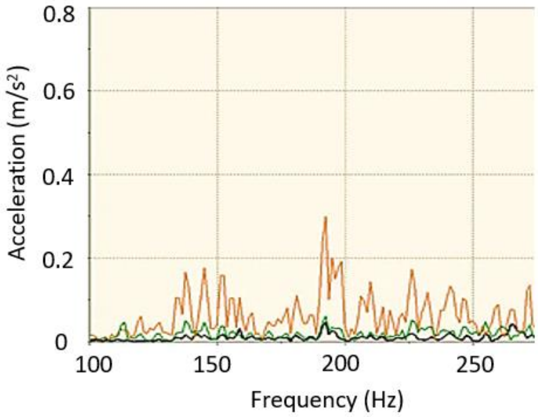
Figure 6. Frequency spectrum of vibration at (a) compressor, (b) power steering and (c) AC pipe during idle condition. The black, green and red lines represent *x*, *y* and *z*-direction respectively.

Tracking condition

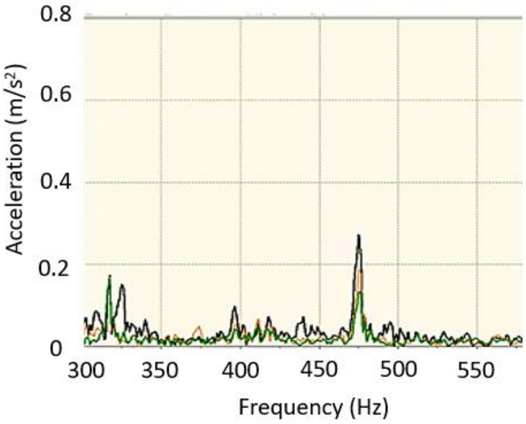
Figure 7 shows the vibration response in *x*, *y* and *z* direction at compressor, power steering pump and AC pipe during tracking condition with the AC turned off. The highest peak amplitude occurs along *x* and *z* directions for AC pipe and compressor. Both highest responses occur within same frequency range which are 400 to 500 Hz. In contrast, the highest response for steering pump occurs at a frequency range of 150 to 250 Hz with substantial response occurring along y direction, as significant peak amplitudes exist when comparing the *x* and *z* directions.



(a)



(b)



(c)

Figure 7. Frequency spectrum of vibration at (a) compressor, (b) power steering and (c) AC pipe during tracking condition (AC off).

Figure 8 shows the vibration responses at compressor, power steering pump and AC pipe as a comparison in idle condition, with the AC turned on. The power steering exhibits the highest vibration response with 1.4 ms^{-2} of *y* direction, in the range of 150 to 250 Hz. for the compressor and AC pipe, however, the vibration dominates along the x and y direction respectively, at the same frequency range of 300 to 350 Hz. The power steering pump contributes the most significant vibration output to the overall HVAC system, which potentially can contribute to the humming-type of noise since both is interrelated.

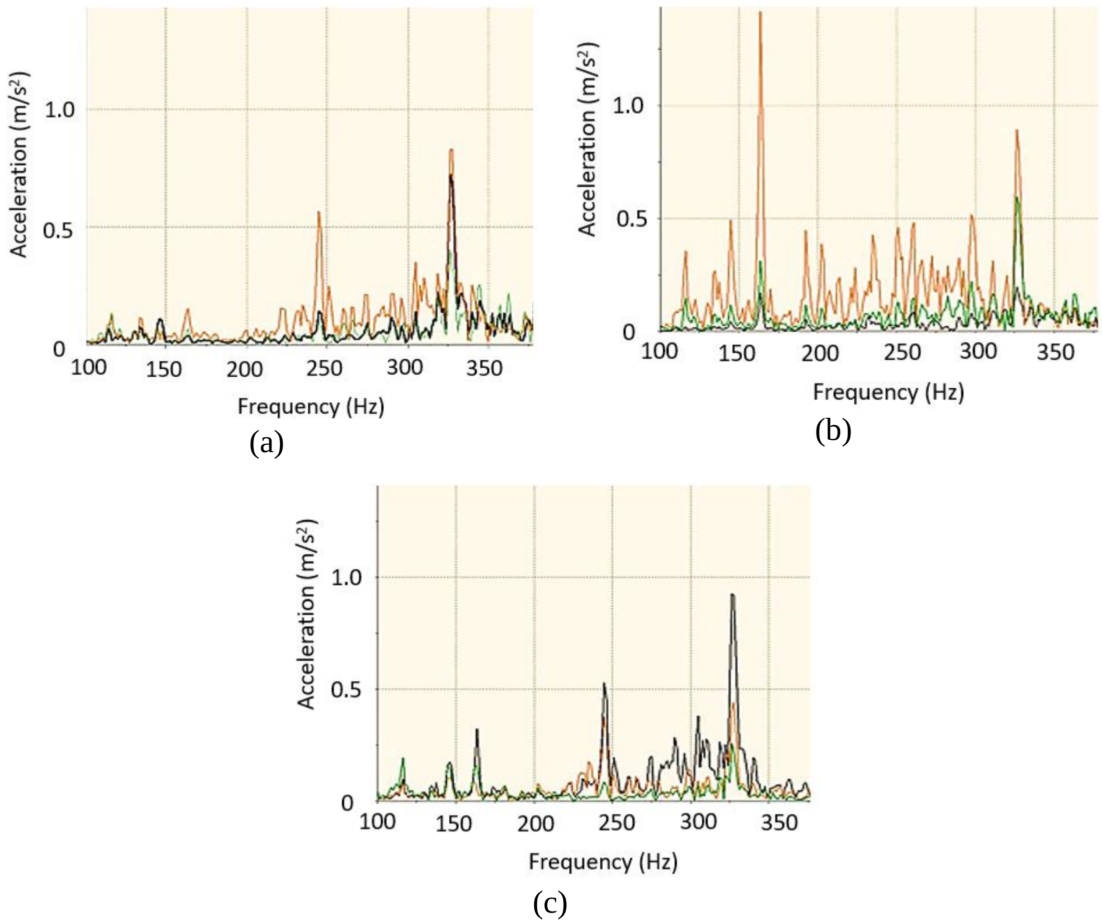
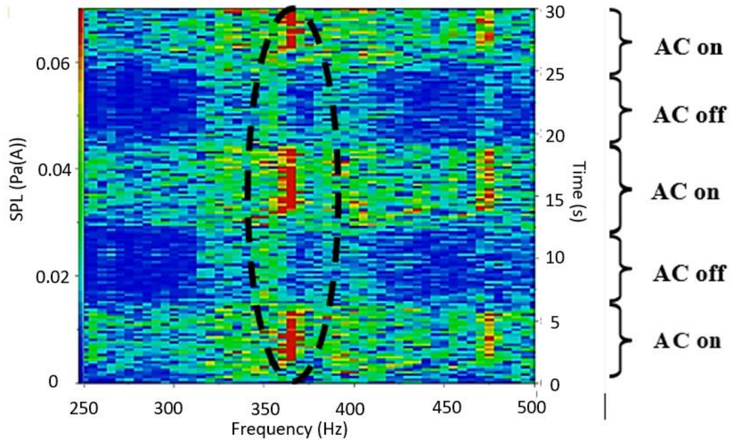


Figure 8: Frequency spectrum of vibration at (a) compressor, (b) power steering and; (c) AC pipe during tracking condition (AC on).

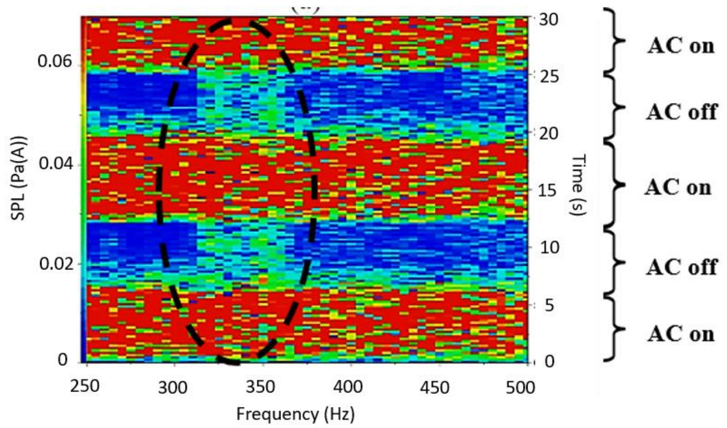
3D Colour Order Analysis

Idle condition

A spectrogram is a visual representation of the spectrum of frequencies of sound signal varying in time. Figure 5 shows the spectrogram of sound pressure level (SPL) for microphones placed at two components - the compressor and the power steering pump - with three repetitive cycles of air conditioner (AC) alternating between on and off. There is high intensity of reddish spot lying within the frequency range of 300-350 Hz when the AC is on, indicating high SPL.



(a)



(b)

Figure 9. SPL from microphone at (a) compressor and (b) power steering pump.

Tracking condition

Generally, a colour map consists of multiple inclined colours spotting the order of mapping or spectrum that represents specific order values determined by the behaviour of any part. The order is used to track the relationships between the vibration response, rpm and frequency of rotation. The first order is set as the reference rotating part, and all other orders are determined subsequently according to the ratio of events per revolution relatively to the first order.

Figure 10 shows the colour map analysis between the compressor, the power steering pump and the AC pipe. On the compressor colour map, there is a large red contour with order of 24. This indicates that the peak of vibration amplitude occurs in a linear pattern between the ranges of 400 to 500 Hz, similar to the previous Sound Diagnosis Method. Similarly, the AC pipe has only one order, which is at order of 24. From subjective hearing, the humming noise can be heard slightly in the sound diagnosis. However, the order map of the power steering pump has multiple red contours representing the order of 12, 24, 36 and 48. This can imply that there are various rotating parts that contribute to a significant vibration. From the Sound Diagnosis method, the order of 12 is diagnosed to have a significant humming sound content compared to the other orders and occurs at the frequency range of 150 to 250 Hz.

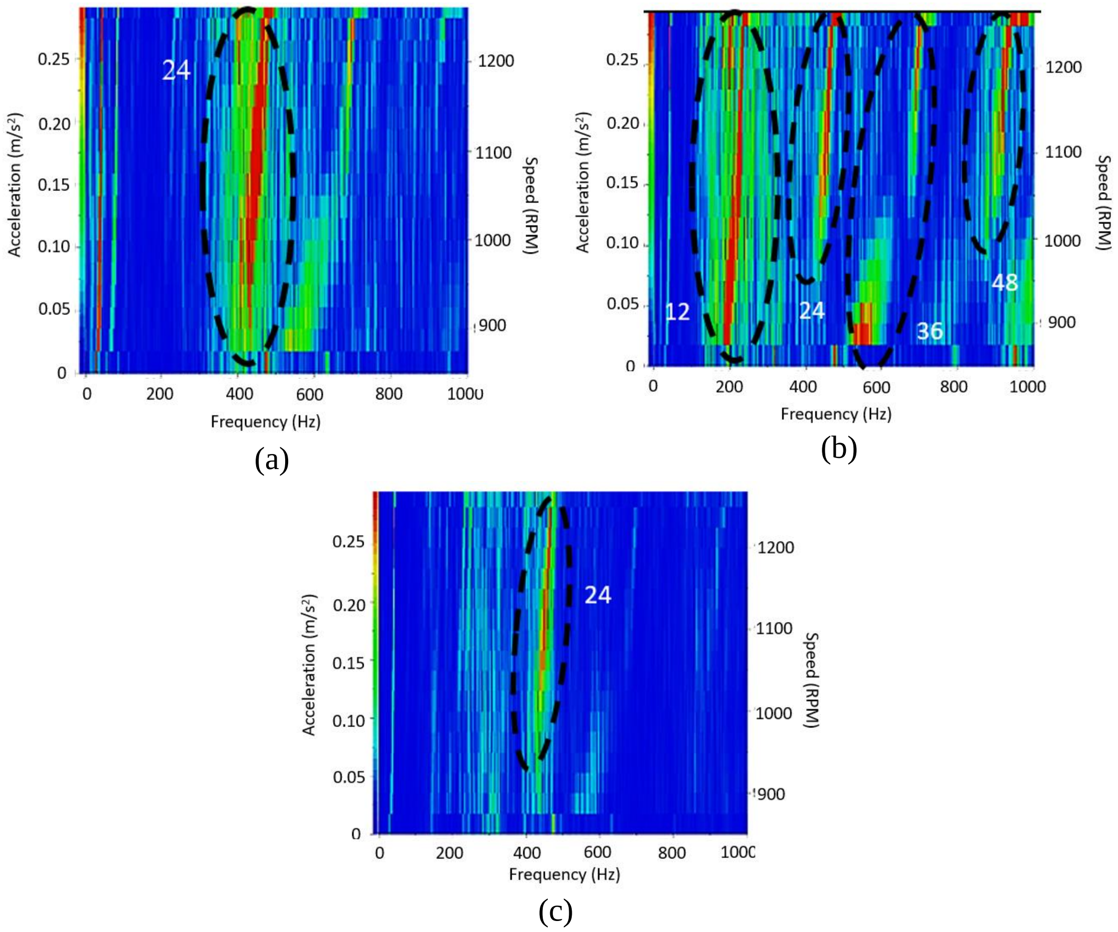


Figure 10. 3D colour order analysis between (a) compressor, (b) power steering pump and; (c) AC pipe (in rpm tracking condition with AC is turned off).

From the figure, at frequency range of 150-250 Hz (i.e. order 11), the power steering pump shows a significant colour contour of red dominance, which indicates the high vibration amplitude compared to the compressor and the AC pipe. This figure supports the result of vibration frequency domain in Figure 8 previously, where at the first order 11, there is a significant vibration amplitude difference between these three components. Meanwhile, at the frequency range of 300-350 Hz (i.e. Order 22), the AC pipe shows a slight colour contour of red dominance, which indicates the high vibration amplitude compared to the compressor and the power steering pump. The second order 22 of 3D colour order contour supports the result in Figure 8, where at the second order 22 frequency range, the vibration of the AC pipe is more significant compared to the other two components. For both frequency ranges (150-250 Hz and 300-350 Hz), when the data is converted to the noise domain using Sound Diagnosis method, the subjective hearing perspective can clearly indicate the humming-type of noise.

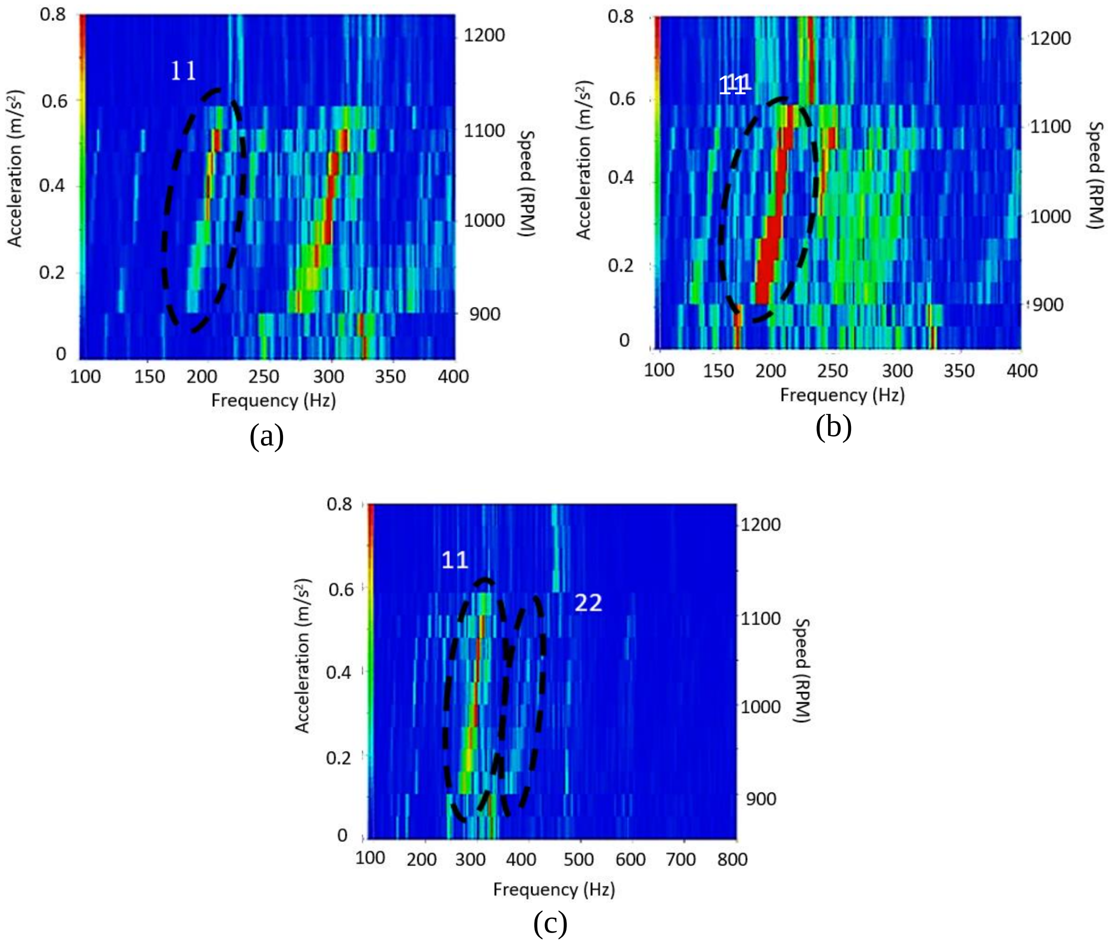


Figure 11. 3D colour order analysis between (a) compressor, (b) power steering pump and (c) AC pipe (in rpm tracking condition with AC is turned on).

Sound Camera Verification

In the previous analysis, the order is carried out by the number of events per revolution of the parts. Similarly in the Sound Camera, the data recorded is calculated based on the number of frames per second [29]. Both approaches will detect and differentiate both stationary and moving noise sources. In this study, the verification of the humming-type noise in term of 3D visualization from the sound camera method is presented. Figure 7 shows the picture of the vehicle engine bay captured by the sound camera. From the figure, it clearly shows that the noise region is concentrated at the power steering pump location when the compressor of the HVAC system is engaged (in idle condition). The frequency range of the sound camera is filtered between 300 to 350 Hz based on the second order (i.e. Order 22) frequency range determined in Figure 9 previously. Based on this measurement, the high level of humming-type noise is shown by the red colour contour in Figure 11 with the maximum noise range of 65.9 dB.

Referring to the vibration amplitude in Figure 8 previously, the highest peak for the compressor and the power steering pump may slightly be affected by the engagement impact of the magnetic compressor clutch, as both components are located in close proximity with each other and share the same belting drive of the engine vehicle. Besides that, from the air conditional pipe vibration plot, there is also a significant large peak amplitude within the same frequency range which most probably is due to the constraint in mounting the setup on the vehicle structure. This result gives a clear insight that the operating vibration of the system being transferred through the compressor and the power steering pump, eventually to the pipe in sequential transmission. This may amplify the vibration signal toward the power steering pump and subsequently creates the humming-type of noise of a vehicle's HVAC system.

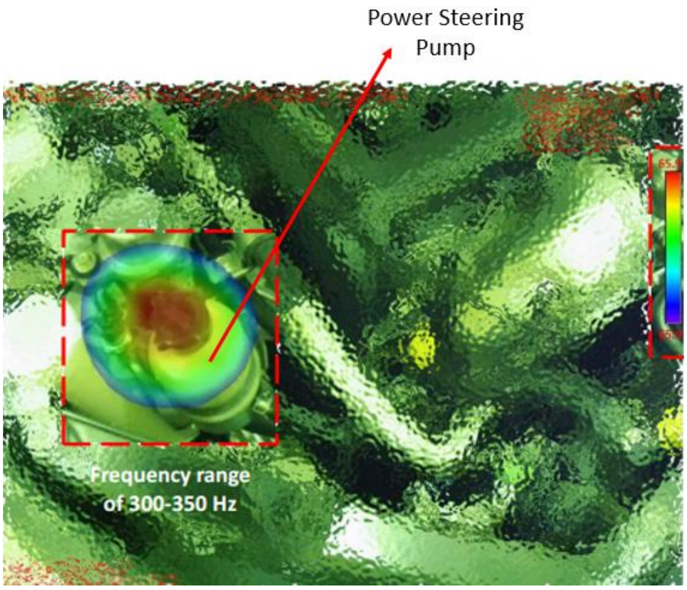


Figure 12. Humming-type noise verification using sound camera method (in idle condition).

CONCLUSION

In this study, the main objective to determine the root cause of the humming-type noise of the vehicle HVAC system components has been achieved. Table 2 shows the summary of the result, in which the power steering pump has been found to have contributed a significant vibration amplitude of 1.8 m/s^2 in the frequency range of 150-250 Hz (i.e. Order 11). This result has also been verified using both 3D colour order and sound camera methods. In terms of subjective hearing perspective, this frequency range has clearly indicated the humming-type noise of the HVAC system components.

Table 2. Result summary of the HVAC system.

Type of noise	Test conditions	Noise frequency ranges	Highest noise contribution parts
Humming	Idle (850 rpm)	300-350 Hz	Power steering pump
	RPM tracking	400-500 Hz	
	(850-1400 rpm)	150-250 Hz	

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