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Suppression of Flow-Induced Noise of a Canister Vacuum Cleaner

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Abstract: This paper describes the modification of a canister vacuum cleaner to reduce flow-induced noise. This research aims to identify the noise source and suppress the noise level of a canister vacuum cleaner experimentally without affecting its suction power significantly. Based on the preliminary results, the noise was mainly contributed by blade passing noise generated by the motor and airborne noise from aerodynamics origin. The blade passing frequency of the motor is 2475 Hz, while the dominant airborne noise occurs at 600 Hz. Two noise reduction methods were introduced: porous expanded polypropylene sound panels and a honeycomb noise filter in a canister vacuum cleaner. A layer of K-flex K-FONIK open-cell applied to the inner wall of the vacuum cleaner showed a 3.7 dB(A) reduction in noise level. In comparison, the honeycomb noise filter reduced the noise level by 3.4 dB(A). When both methods were implemented concurrently, the overall noise level was successfully reduced from 73.2 dB(A) to 65.8 dB(A), achieving a total reduction of 7.4 dB(A). The vacuum cleaners suction power was tested after the modifications, and the results showed only a 0.001 Watts or 0.93% reduction in suction power.

Keywords: Vacuum cleaner, K-flex K-FONIK open-cell, honeycomb noise filter

1. Introduction

In recent years, the household appliance industry has focused its research goals on reducing noise emissions due to the rising awareness of noise pollution and the increasing demand for a higher quality lifestyle. Research and surveys have shown that people are not satisfied with the high noise emitted from their household appliances. They are willing to spend more money to obtain a better user experience as vacuum cleaners are very frequent in this modern age. The loud noise produced by vacuum cleaners can be disturbing and, at the same time, annoying for the user as well as the people nearby. This noise will interfere with the communication between humans and cause disturbance to other people and result in loss of focus. Hence, this paper describes the modification of a canister vacuum cleaner experimentally to minimize flow-induced noise without affecting its suction power significantly.

The vacuum cleaner emits noise due to many separate but interacting noise generating mechanisms. A noise

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spectrum characterized by broadband noise with discrete frequency tones is produced by all the noise generating mechanisms combined. Rotational noise is the spectra with discrete frequency tones related to the rotational frequency (RF). In contrast, Non-rotational noise is the spectra with prevailing broad and noise and discrete frequency tones unrelated to the rotational frequency. The rotational noise of aerodynamic origin is caused by pressure fluctuations due to the periodic fluctuation of the air forces [1]. In the blower, the blades move and cut through the air, thus thrust and drag forces induced on them, and also the impulsive interaction of the blades with inflow distortion are the causes of the rotational noise. The non-rotational noise is caused by the non-uniform steady flow fields, the interaction between the turbulent flow and the rigid structure, and the vibration of the housing. Furthermore, the changes of the flow passages, the flow hitting on the obstacles, for instance, diffuser vanes and rotor blades, contribute to the non-rotational noise. The non-rotational noise level depends on the vacuum cleaner housing's flow velocity, dimensions, and design.

Tadina et al. designed a motor enclosure to isolate the noise generated by the motor [2]. The design consists of a capsule housing, an upper and bottom suspension rubber, foam, and a capsule cover. The motor enclosure creates a channel structure to direct a portion of the exiting airflow into a designed flow chamber that allows the air to turn at different angles before exiting the enclosure. The noise reduction concept lies in the airflow turning more than 360 degrees in the motor enclosure. When the airflow is turning, the internal reflections of sound waves occur and thus causing the absorption of energy in the sound waves. In addition, the motor's vibration is reduced by the rubber suspension. When the motor is only in contact with the suspension, the rubber act as a damper. Therefore, the vibration of the motor is absorbed partially and at the same time will not transfer directly to the vacuum cleaner’s body. As a result, the noise due to the motor's vibration is reduced. This experiment results showed that the design reduces the noise level by 12dB, which is a 25% reduction of vibration level on the motor.

The airflow is a significant noise source because the air moves at high velocity from inlet to exhaust when the suction fan is turned on. Its interaction with the surfaces and obstacles creates a tremendous amount of noise. Hence, the typical noise-reduction method slows down the airflow and alters the path. The airflow paths are different for different models and types of vacuum cleaners; thus, the noise suppression methods vary.

The exhaust airflow is one of the critical elements in the contribution of airflow noise. Herron invented a cartridge that can be installed in a canister vacuum cleaner [3]. Unfortunately, this cartridge interferes with the airflow when exiting the vacuum cleaner. The cartridge consists of two parts, and each part is a well-designed array of baffle plates that are interleaved with the other part when both are combined in a juxtaposition for installation. When the air is forced to go in the baffle plates, the airflow undergoes multiple direction changes, thus losing part of its energy. As a result, the noise generated by the exhaust airflow is reduced.

Buratti, Moretti, and Urbani managed to reduce the noise of a wet vacuum cleaner with two modifications [4]. First, they analysed the results from their noise source measurement and concluded that modifications on the exhaust flow paths reduce the noise caused by the pressure variation of airflows. Firstly, they identified that the geometry at the outlet pipe of the vacuum cleaner has two elbow curves and one shrinkage, which can cause an acceleration in exhaust air velocity and consequently a higher noise level. Therefore, the outlet pipe is modified to create a flow path without angles. Then, the exhaust area is increased by creating 32 holes in the vacuum cleaner housing, increasing the exhaust area from 9.6 cm2 to 25.1 cm2. After the modifications, the sound power level is reduced from 96.7 dB(A) to 93.2 dB(A).

The noise produced by the fan blade can be categorized into two sources: broad-band noise and discrete frequency tone. The broad-band noise is caused by the turbulent flow of the incoming air, while the discrete frequency tone results from the noise generated by the rotating blade at blade passing frequency (BPF). The dimensions, shape and angles of the fan blade can be modified to achieve lower noise, and sometimes at the cost of reduced performance, thus the optimum point has to be determined.

Brungart and Lauchle reduced the noise of a handheld vacuum cleaner by using a modification approach [5]. In the experiment, the tones of the noise generated are identified, and the high amplitude sound source is coming from the fan blade passing frequency of the working fan. Firstly, the volute of the working fan, also known as the stone shield, is modified and reshaped to reduce the pressure fluctuations due to the interactions between the working fan and the stone shield. This modification alone has successfully reduced the sound power level by 4 to 8 dB at that particular frequency, while the A-weighting sound power is reduced by 2 dB. Next, the addition of fan blades is introduced, the number of fan blades is increased from 6 to 9 to reduce the in-phase interaction between the fan blades and the corners of the stone shield. As a result, the A-weighted sound power level is reduced by 4 dB.

Part et al. designed a new brush nozzle with a separation block, brush drum and rotary fan to reduce the emitted noise [6]. The brush nozzle is attached to the vacuum cleaner, and its function is to collect the dust from its widespread inlet. Firstly, the noise at the cost of losing part of the suction power is reduced, and then the suction power is increased to compensate for that loss. By shortening the fan blade in the rotary fan, the sound power level is reduced by 4 to 5 dB, and at the same time, the suction power is reduced as well. Then, the separation block is replaced with a new modified block with the specific curvature and width designed and verified numerically. As a result, the suction power quantified by the fan's rotational speed is increased by 30%. In a nutshell, the overall noise level is reduced without sacrificing the loss of suction power.

Krishna et al. reduced the aerodynamic noise generated by the fan blades by replacing the original straight radial fan blades with backward inclined airfoils blade [7]. In addition, the blade's number was also reduced from 10 to 7 and bell mouth entry was adopted at the inlet. The noise levels of the new fan blade with various digits of NACA 65 airfoils were simulated using the FLUENT package in Computational Fluid Dynamics (CFD) simulations. The sound pressure level ranged from 65.4dB(A) to 74 dB(A), while the lowest overall sound pressure level was 65.4dB(A). The flow rate through the new fan blade is approximately $0.367m^3/s$. Compared with the flow rate for the original blades, it is increased by 15.4%. Next, the redesigned fan blade is tested in a semi-anechoic chamber. The overall noise reduction is 12.8 dB(A)

Honeycomb or hexagonal cellular structures were widely used in engineering applications due to their controllable effective mechanical properties and high strength to weight ratio. Several studies showed that a panel with perforated front-facing and impervious back skin could act as a good sound absorber over a narrow frequency band due to the Helmholtz resonator effect that utilized the perforated hole the air trapped in the honeycomb cell [8]. Studies have also proved that it was possible to spread this frequency band by substituting porous skins for perforated ones [9]. Some jet engines were made quieter by this concept by using cowlings with stainless steel honeycomb and perforated skins. This paper applied honeycomb structures on the vacuum cleaner to reduce the emitted noise.

2. Methodology

2.1 Experiment Setup

The overall performance of a vacuum cleaner can be defined by its suction power, as it represents how well the device sucks up the dust. The measurement of the inlet air velocity of the vacuum cleaner was carried out with Victor 816B Digital Anemometer. The vacuum cleaner was switched on, and the anemometer fan blade was placed at the vacuum cleaner's air inlet as shown in Fig. 1. The measurements were made before and after the modifications.

Fig. 1 - Air velocity and suction power measurement

The measurement of the sound pressure level of the vacuum cleaner in operating mode was carried out according to ISO 3744, which describes the engineering method in sound measurement. This standard supports all noise sources such as steady, isolated bursts, fluctuating and unsteady noise sources. According to ISO 3744, the measurement can be done outdoors and indoors, with one or more sound-reflecting planes present, for instance, floor. Also, the standard requires that the instrumentation system meet the requirements of IEC 61672-1:2002, class 1. The noise measurement for vacuum cleaner was carried out with Bruel & Kjaer Hand-held Analyser Types 2270 and Bruel & Kjaer's Transducer Electronic Data Sheet (TEDS) microphone. The Bruel & Kjaer hand-held analyser hosts several applications, such as fast Fourier transformation, logging, frequency analysis, signal recording, and building acoustics.

The experiment set-up was following International Electronics Commission (IEC) standard, as shown in Fig. 2. The microphone was pointed directly towards the noise source in free field measurement. For optimum accuracy, the angle between the microphone and the noise source was set to 0 degrees. In addition, The Bruel & Kjaer hand-held analyser was mounted on a tripod to avoid interference from the operator that blocks the sound wave as well as causing reflections that lead to inaccuracy of measurement. The previous studies show that reflections of the sound wave from humans can cause errors up to 6 dB(A) at 400Hz when the measurement was near a human body in one-meter range.

The vertical height of the microphone from the object was set at 1.60 metres as this is the average human height of Malaysian. The horizontal distance between the microphone and the vacuum cleaner was 0.45 metres. The distance remained a fixed variable as any alteration would cause the measurement to be inaccurate. The data was then transferred to the Bruel & Kjaer Measurement Partner Suite software, and the FFT was plotted in Bruel & Kjaer FFT Analysis Software BZ-7230. Since this experiment focuses on human hearing, thus the frequency span was set at a range of 0 Hz to 20k Hz as this is the human audible frequency range, while the time for measurement was set at a constant 15 seconds.

The vibration and rotational speed of the motor were measured to support the noise identification process and FFT analysis. The accelerometer type 4508 was used to measure the motor's vibration in the vacuum cleaner. The accelerometer was mounted on the motor in operating conditions to measure its vibration. The motor's rotational speed was measured by TPI 505 Optical & Contact Tachometer. The contact tach operation method was used because the optical tach operation failed to produce any helpful result as the exposed surface for the optical tachometer to detect the reflective tape is limited due to the structure of the motor. Thus, the contact tach technique was applied by holding the cone-shaped contact wheel against the rotating end of the motor. The rotational speed of the motor was recorded in RPM. The sound pressure level measurement and FFT analysis were performed before and after applying the noise abatement methods.

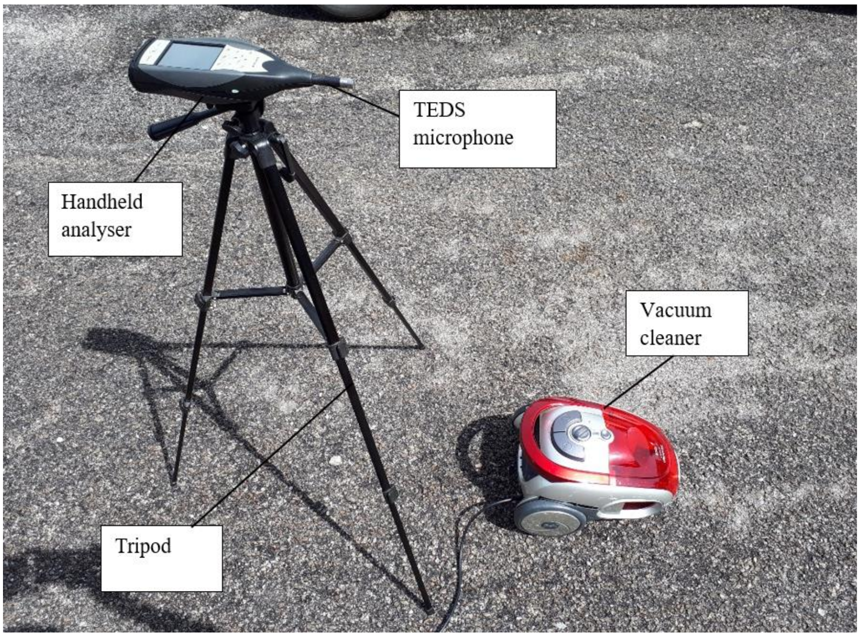


Fig. 2 - Sound pressure level measurement setup

2.2 Adding Sound Absorptive Material

Adding sound absorptive material is a practical approach to suppress noise. In general, sound absorptive material can be installed in the inner wall of a vacuum cleaner, which is ideal for the vacuum cleaner. There are several casings in the complete structure of a vacuum cleaner. However, the installation of sound absorptive material might affect the vacuum's airflow, thus causing a drop in performance. Therefore, the suitable location to install the sound absorptive material and the amount of the sound absorptive material applied were determined through optimization. Different amounts of sound absorptive material were installed, and the suction power, represented by the inlet air velocity and the corresponding noise reductions, were measured repeatedly. Take a fully covered inner wall as 100% coated, 80% coated, 60% coated, 40% coated and 20% coated was tested for their corresponding performance and noise reduction achieved. The K-flex K-FONIK open cells were used as the sound absorptive material and the 100% coated inner wall setup was shown in Fig. 3.

(a) (b)

Fig. 3 - (a) 100% coated inner wall; (b) 700% coated inner wall with K-flex K-FONIK open cell

2.3 Replacing Filter with Honeycomb Liner Noise Filter

Honeycomb liner reduces noise by dissipating acoustic energy with rapid alternating movement of air caused by the honeycomb's perforation structure. It was identified that the original outlet filter does not help reduce noise. Two sound measurements were taken for the vacuum cleaner with and without the outlet filter, and there was no significant difference in the sound pressure level. Therefore, the presence of the filter was solely for outlet air regulation purposes. Thus, the honeycomb liner filter was applied to reduce the vacuum cleaner's noise in operating conditions. The honeycomb liner was designed and built following the findings from the research done by Huang et al. [10]. According to Huang et al., the larger the diameter, d, of the perforations, the smaller the absorption coefficient. If the thickness, t, of the perforations increases, then the acoustic performance deteriorates, and the maximum absorption coefficient shifts to a lower frequency. Changing the length of the backing cavity, D, does not change the maximum absorption coefficient by too much though its peak shifts to a lower frequency. Thus, a specific design parameter is needed for a targeted noise frequency. Since the noise generated from the vacuum cleaner ranges from 2000 Hz to 10000 Hz, the proposed honeycomb perforation has a thickness of 0.4mm, a diameter of 0.4mm and a backing cavity of 50mm. The prototype was drafted in SolidWorks and printed using a 3D Printer using PLA material. The drawing of the liner is shown in Fig. 4.

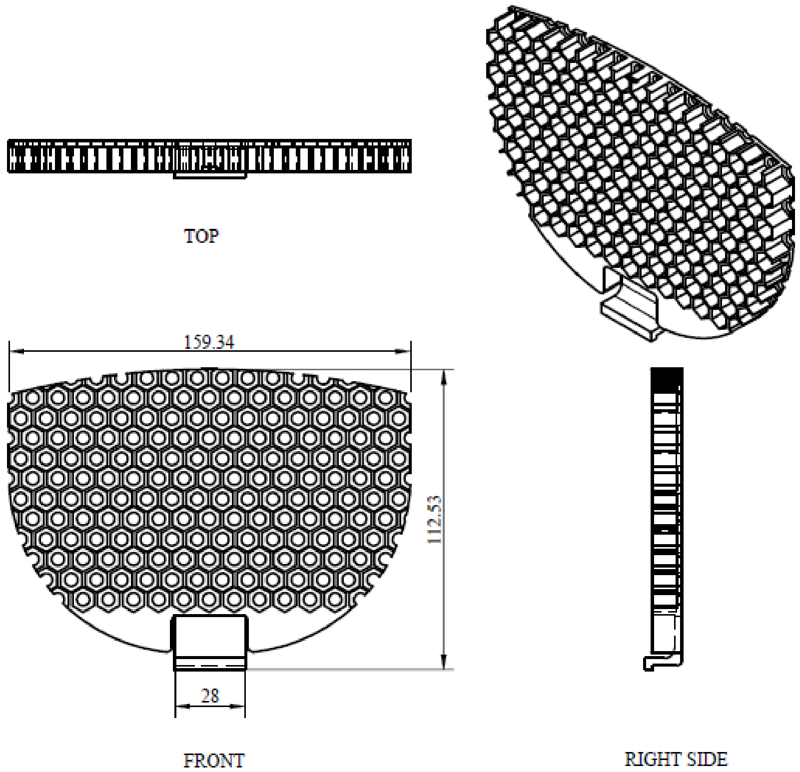


Fig. 4 - Drawing of the proposed honeycomb liner noise filter

3. Results and Discussion

3.1 Noise Source Identification

The inlet velocity of the vacuum cleaner in the operating condition was measured at 9.47 m/s, which is equivalent to the suction power of 0.108 W before the modifications were made. In addition, the sound pressure level of the vacuum cleaner prior to the modifications in operating condition was recorded at 73.2 dB(A).

The acoustic characterization is an effective method for noise identification [4]. The vacuum cleaner was categorized into five configurations: full case, outer case, controller case, motor case, and naked motor, as shown in Fig. 5. The sound pressure level FFT for the various configurations before modification was plotted in Fig. 6 to identify the sound source.

From the results, the blade passing noise generated by the motor was identified by tracking the peaks at the computed blade passing frequency of 2475 Hz and its superior harmonics, which are 4950 Hz and 9900 Hz. There are noticeable amplitudes at the Blade Passing Frequency's harmonic of 7425 Hz and 12375 Hz. The most substantial discrete tonal noise is at 4950 Hz with a peak of 71.14 dB(A), followed by 66.15 dB(A) at 9900 Hz, and 65.56 dB(A) at

2475 Hz. These peaks' identification was further supported by the vibration FFT graph of the motor, where the significant peaks match with the sound pressure level's peak at 2475 Hz, 4950 Hz and 9900 Hz. These peaks are the dominant noise that contributes to the overall noise emission of the vacuum cleaner. By observing the Full Case FFT graph, the sound pressure level at a higher frequency is relatively lower than the lower frequency range. When the cases were used to cover the motor layer by layer, each enclosure suppresses the motor's vibrations at a higher frequency range. The most significant suppression occurs at the 'Full case' configuration. This explains the contrast between large amplitude and low noise levels at a higher frequency range.

Moreover, at the frequency range of 16000 Hz to 20000 Hz, the vibration amplitude increases linearly, but the noise level shows steady declination. This indicates that vibration at 16000 Hz and above does not contribute to overall noise emission by the vacuum cleaner. However, the effect of motor vibration on overall noise level is significant at the frequency range of 2500 Hz to 15000 Hz, where the blade passing frequencies have been identified and verified with the computed rpm and vibration FFT graph. Since the dominant noise peaks are identified, the reduction of these dominant noise peaks will undoubtedly suppress the overall noise level of the vacuum cleaner in operating conditions. The graph was analyzed to discover the relationship of each configuration with the noise emitted.

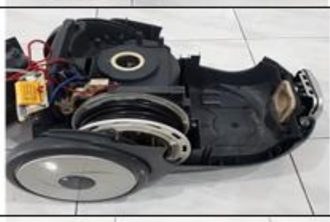
Designated term	Configuration
Full case	
Outer case	
Controller case	
Motor case	
Naked motor	

Fig. 5 - Various configurations of the vacuum cleaner

The noise is reduced ascendingly from the naked motor, motor case, controller case, outer case, and lastly, full case by comparing the five types of configurations. These reductions are caused by the enclosing effect of each of the cases. They all act as an enclosure to block the noise generated by the motor. Nonetheless, the reduction levels are not the same for each configuration. The most significant noise reduction is at ‘full case’, with a maximum of around 20 dB(A) reductions, and the reduction is more noticeable at a higher frequency range, from 6000 Hz to 20000 Hz. As for 'outer case' and 'controller case', two of them show a similar FFT graph, but there are pronounced noise reductions all over the frequency span, with a maximum reduction of approximately 12 dB(A). The 'motor case' reduced the noise distinctively at 2100 Hz to 2800 Hz and 8000 Hz to 10000 Hz. It shows an identical graph with 'naked motor' at other frequencies. The 'naked motor' graph tops all the other configuration's FFT graph as it does not have any isolation and cover. Now, installing the sound absorptive material directly at the 'naked motor' is suggested for the best soundproofing effect because it is the noisiest configuration. However, the 'naked motor' itself does not possess an inner wall for the installation. This leads to its successor, the motor case. There is an inner wall for installation at the 'motor case' configuration. From the literature review, there is the possibility that the installation of sound absorptive material at the inner wall would lower the performance of the vacuum. Thus, an optimum amount of sound absorptive material must be determined.

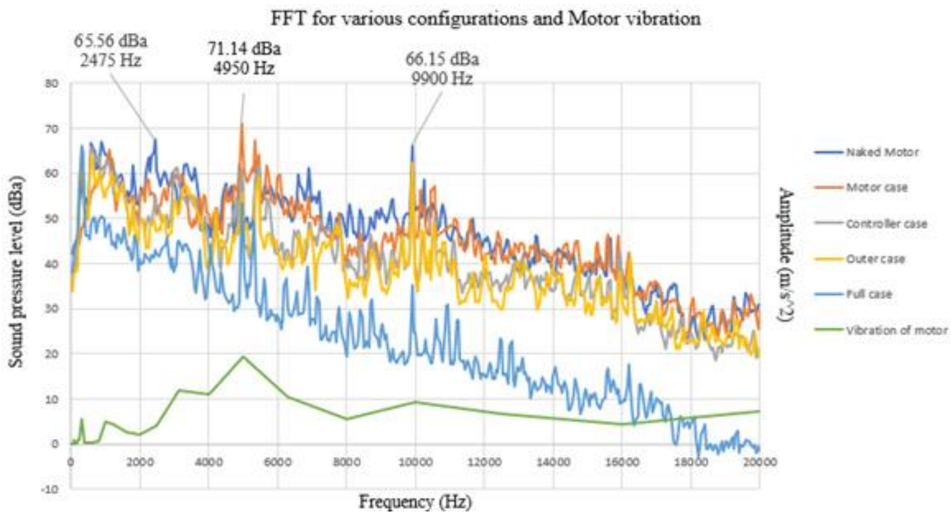


Fig. 6 - Sound pressure level FFT for various configurations from 0 to 20 kHz

There are two noticeable peaks at the low-frequency range of 1 to 1000 Hz. The zoomed-in FFT graph is studied as shown in Fig. 7. The first peak occurred at 300 Hz, with the SPL of 66.25 dB(A), while the second peak occurred at 600 Hz, with the SPL of 65.85 dB(A). According to the motor vibration FFT graph (Figure 7), a vibration with an amplitude of 5.64 m/s2 is detected at 300 Hz, matching the noise FFT graph at the same frequency. Thus, it can be concluded that the motor vibration generated the noise at 300 Hz. However, at 600 Hz, the vibration amplitude of the motor is only 0.15 m/s2, near zero. The comparison indicates that the noise at 600 Hz is not generated from motor vibration but is caused by airborne noise. The airborne noise only can be suppressed effectively when the entire enclosure is covered. A small opening will cause the transmission loss to decrease dramatically. The full case condition is effective in suppressing airborne noise but not in suppressing motor noise. Hence, the SPL before 400 Hz remain high, but the SPL level after 400 Hz decreases dramatically.

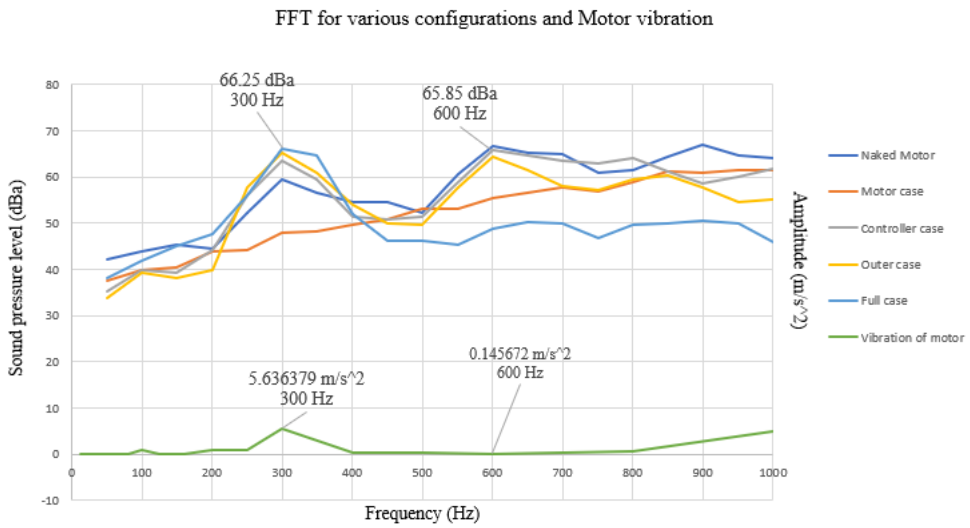


Fig. 7 - Sound pressure level FFT for various configurations from 0 to 1000 Hz

3.2 Effect of Sound Absorptive Material

Figure 8 shows the acoustic performance graph of various types and dimensions of K-FONIK open cell material (K-flex Acoustic Insulation: Solutions for acoustic comfort, 2017). From the FFT analysis, the dominant peak of the noise generated by the motor is at 4950 Hz. K-FONIK OPEN CELL 160, 25mm, yields the highest sound absorption coefficient at 4950 Hz. Thus it was used to be used in this modification. Theoretically, the sounder absorptive material installed, the better the soundproofing effect. Nonetheless, the airflow will be affected by the installation of extra material, hence lowering the vacuum cleaner's performance. This trade-off was studied in this experiment to obtain the optimum amount of sound absorptive material to be applied.

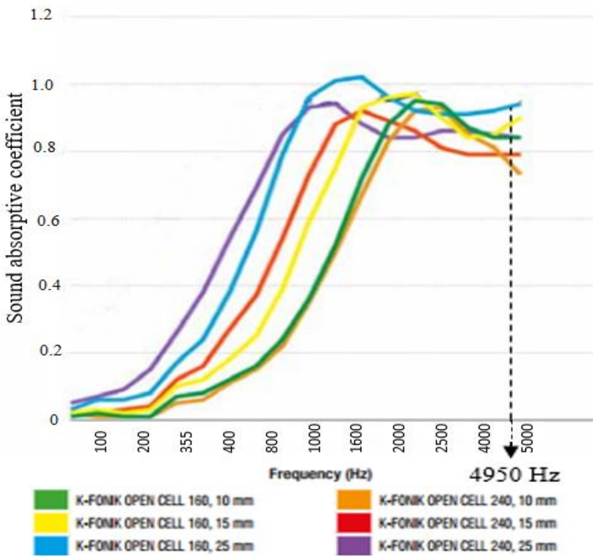


Fig. 8 - Acoustic performance of various types and dimensions of K-FONIK open cell

Fig. 9 shows the effect of the coated area with K-FONIK open cell on the inlet air velocity. The results showed that the inlet air velocity decreases as the percentage of coating increases, while the effectiveness of the noise suppression increase with the amount of coated area. The optimum percentage of sound absorptive material is at 70%, with an estimated noise reduction of 3.8 dB(A).

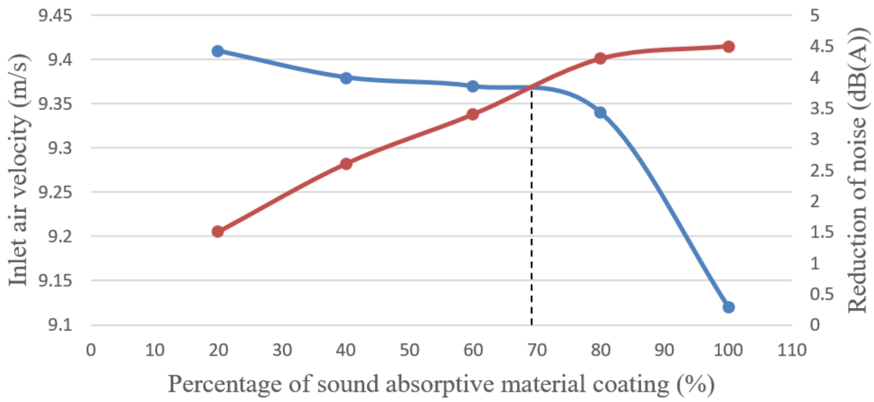


Fig. 9 - The effect of total coated area on the inlet air velocity

The sound spectrum FFT was plotted for the vacuum cleaner with and without K-FONIK open cell, as shown in Fig. 10(a). The sound peaks are generally reduced, ranging from 2 dB(A) to 15 dB(A) at different frequency ranges. The FFT graph in Fig. 10(a) was magnified at range 4000 Hz to 6000 Hz and 9500 Hz to10500 Hz as shown in Fig. 10(b)-(c) to show the effect on the existing peaks. The results show the noise reduction of 7.71 dB(A) at 4950 Hz and 8.65 dB(A) at 5300 Hz, respectively. The peak at 4950 Hz is one of the dominant noises that contributed to the overall noise level emitted by the vacuum cleaner. Thus, reducing this peak leads to attenuation of the overall sound pressure level of the vacuum cleaner when operated. Another dominant noise peak at 9900 Hz has been lowered from 35.34

dB(A) to 24.32 dB(A), achieving a noise reduction of 11.02 dB(A). The peak was shifted slightly from 9900 Hz to 9850 Hz from the observation. The overall sound pressure level showed a 3.7 dB(A) reduction with 70% of the sound K-FONIK open-cell coatings, close to the expected sound attenuation.

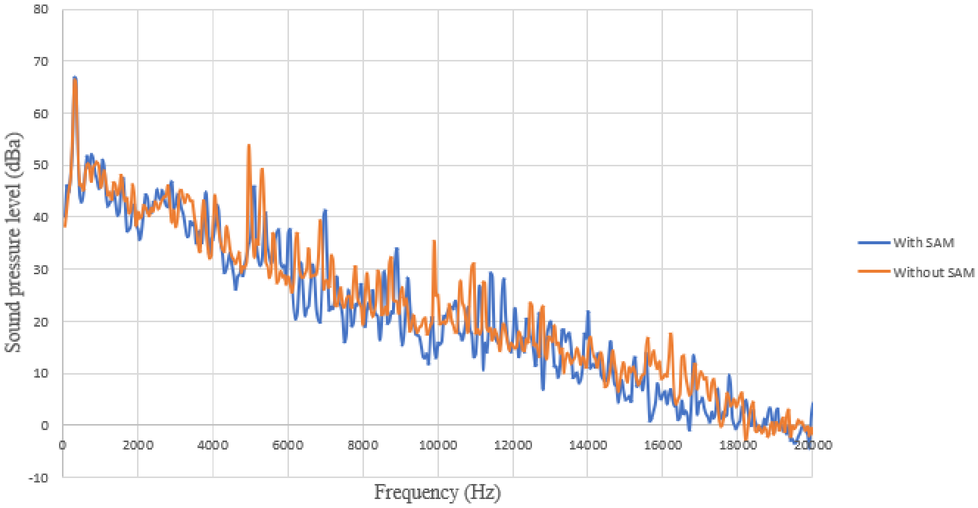


Fig. 10(a) - Effect of SAM coating on the sound pressure level

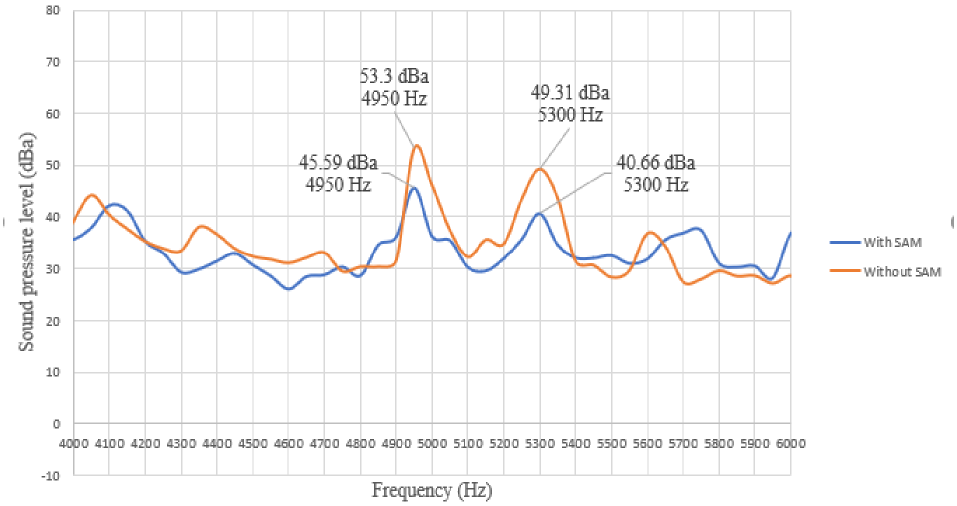


Fig. 10(b) - Effect of SAM coating on the sound pressure level at 4950 Hz and 5300 Hz

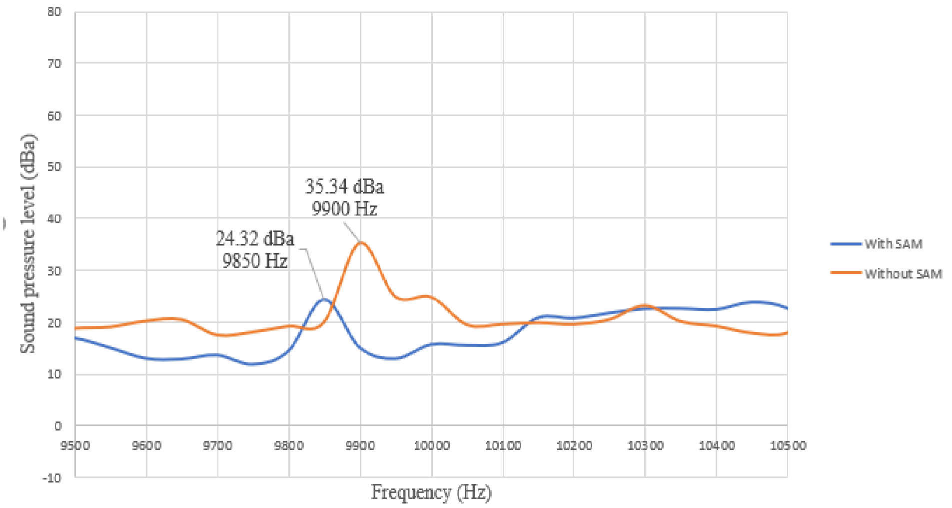


Fig. 10(c) - Effect of SAM coating on the sound pressure level from 9500 Hz to 10500 Hz

3.3 Effect of Filter Replacement with Honeycomb Liner Filter

The airborne noise was recorded at 600 Hz based on the frequency spectrum analysis. The dimensions of the honeycomb filter are designed based on the research done by Toyoda et al. (2011) and Huang et al. (2016). The studies showed the relationship between dimensions and its corresponding sound absorptive coefficient at different frequencies. Two layers make up the honeycomb liner. The first layer is the perforation layer, a flat plate with small holes. Based on the finding of Toyoda et al. (2011), a 4 mm thick perforation plate yields the highest sound absorptive coefficient, α=0.9, on the sound frequency of 600 Hz. The results also showed that the perforation diameter of 5 mm yields the highest sound absorptive coefficient, which is α=0.87 on the sound frequency of 600 Hz. For the second layer, which is the honeycomb-shaped layer, the optimum thickness to suppress 600 Hz sound is 0.015 m. The model was drafted and printed out with a 3D printer with these dimensions, as shown in Fig. 11. The prototype is then attached to the exhaust port of the vacuum cleaner. Fig. 12 shows the sound pressure level from 0 to 1000 Hz for the vacuum cleaner with and without the honeycomb noise filter. The graph shows that the 600 Hz airborne noise is reduced from 48.68 dB(A) to 41.04 dB(A), achieving an attenuation of 7.64 dB(A). In addition, the noise origin from motor vibration at frequency of 300 Hz shows a slight reduction of 3.85 dB(A), from 66.25 dB(A) to 62.4 dB(A). The noise filter reduced the entire noise spectrum from 73.2 dB(A) to 69.8 dB(A), achieving a reduction of 3.4 dB(A) as in Fig. 12.

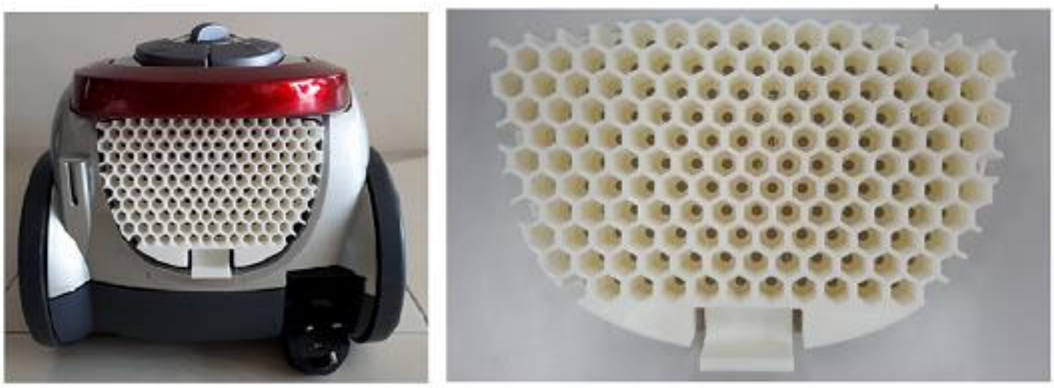


Fig. 11 - Honeycomb noise filter prototype

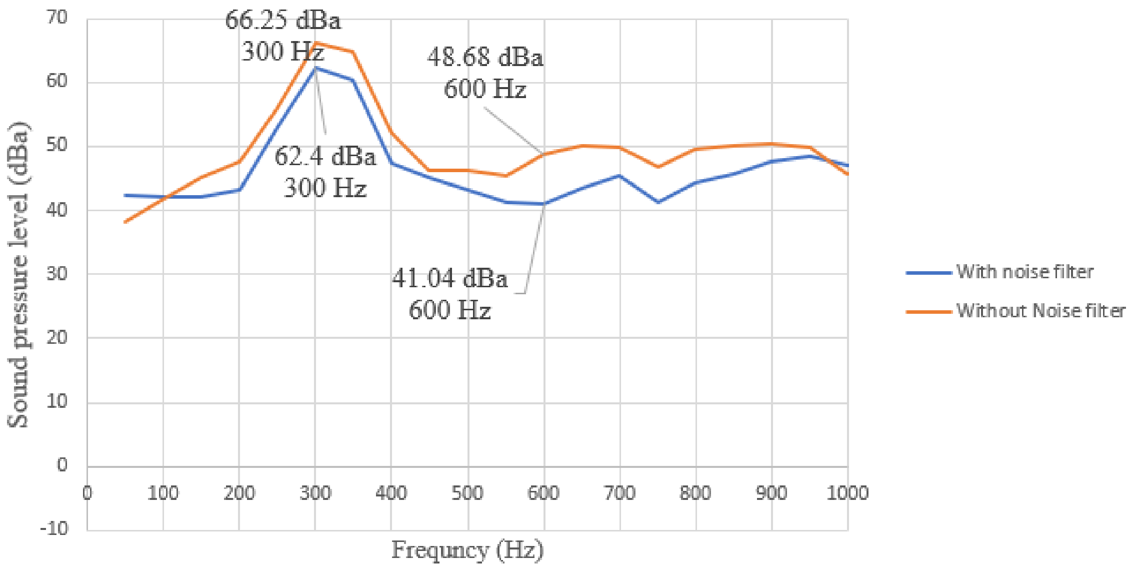


Fig. 12 - Effect of frequency on the sound pressure level

Since both reduction methods have shown promising results, both sound absorptive material and noise filter are implemented together, and the overall noise attenuation was tested with the same experimental setup. As a result, total noise attenuation of 7.4 dB(A) is attained with both proposed methods implemented, based on the original noise level before modification, which is 10% noise reduction in SPL or equivalent to 57.44% reduction in sound pressure was achieved. In addition, the air velocity at the inlet was measured once again to check if the vacuum cleaner's performance had dropped after implementing the proposed noise reduction methods. As a result, the inlet air velocity dropped from 0.108 W to 0.107 W, reducing 0.001 W or 0.93%.

4. Conclusions

The noise distribution of the canister vacuum cleaner was dominated by blade passing noise and airborne noise. The blade passing frequency was identified as 2475 Hz, and the airborne noise was recorded at 600 Hz. The use of K-flex K-FONIK open cell suppressed the noise level from 73.2 dB(A) to 69.5 dB(A), with a reduction of 3.7 dB(A) when 70% of the area are coated on the inner wall. In addition, the honeycomb liner noise filter reduced the overall noise level from 73.2 dB(A) to 69.8 dB(A), achieving a reduction of 3.4 dB(A). With both effects of the K-flex K-FONIK open cell and the honeycomb liner noise filter, the overall noise level has been suppressed from 73.2 dB(A) to 65.8 dB(A), with a total noise attenuation of 7.4 dB(A). The reduction of the suction power after the modification was not significant, with only a 0.93% reduction in suction power.

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