



The Sixteenth International Congress on Sound and Vibration

Kraków, 5-9 July 2009

EXPERIMENTAL ACOUSTIC CHARACTERIZATION OF A WET VACUUM CLEANER

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The aspiration unit of a domestic cleaner is one of the most noisy appliance used in homes. The complex combination of noises which have various origins requires a detailed acoustic characterization, aimed to find the kind of the issued components able to improve the acoustic performances. The sound power levels derived from the various operating velocities of the cleaning appliance were firstly evaluated by means of acoustic pressure measurements. The appliance was analyzed in different configurations, in compliance with the measurement procedures foreseen by the UNI EN ISO 3744 standard. This analysis was carried out in order to isolate the contribution given by the various elements. In order to further detail the acoustic characterization of the cleaning appliance and to verify if there are discreet noise tones at specific frequencies, a narrow band analysis was carried out. The analysis allowed to identify various typologies of noise source such as the aerodynamic contribution of the air flux inside the pipes and the generation of noise due to the rotation of the coupled blades on the rotor. Mechanical noise sources are also present, due to the friction of the brushes, the bearings and the unbalanced masses; finally periodical fluctuations of the magnetic field between the stator and the rotor causes the electromagnetic noise. The detailed study on the appliance and the research in Literature allowed to suggest potential improvement solutions for noise reduction.

1. Introduction

The vacuum cleaner is one of the most powerful noise source among the household appliances. A centrifugal fan is commonly used to create the pressure rise able to suck up dust into the device (figure 1).

The suction unit is a complex source of noise. This is partially aerodynamic, mechanical and electromagnetic in origin^{1,2}. All noise generation mechanisms produce a noise spectrum characterized by broadband noise with pronounced discrete frequency tones. Spectra with prevailing discrete frequency have relation with the rotational frequency (RF) and are indicated as tonal or rotational noise; spectra with prevalent broadband and tonal non-rotational noise are given by turbulent or non-rotational noise³. Total emitted noise is given by rotational and non-rotational noise.

Rotational aerodynamic noise is the result of pressure fluctuations caused by periodic variations of fluid forces induced between the fan impeller blades and the air deflections nearby fixed obstacles. The regular distribution of these obstacles (rotor teeth, diffuser vanes, etc.) causes pressure pulsations in the surrounding area. The emitted noise is pronounced at the blade passing frequency (*BPF*), the teeth passing frequency (*TPF*) and their higher harmonics. The tonal frequency is given by the equations $f_{BPF} = z \cdot n$ and $f_{TPF} = z_T \cdot n$ (z is the number of rotor blades, z_T is the number of the electric motor rotor teeth, n is the rotating speed).

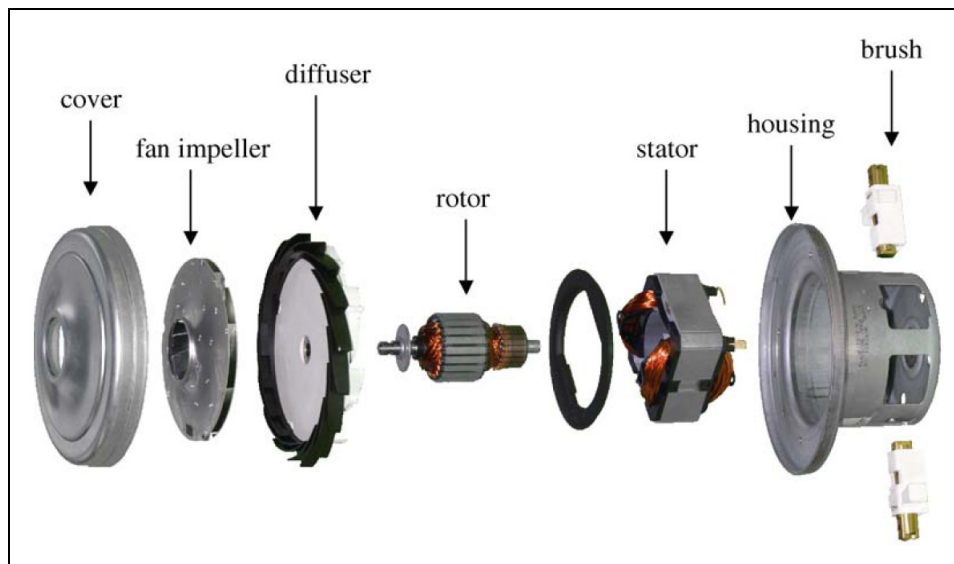


Figure 1. Centrifugal fan parts⁴.

Non-rotational aerodynamic noise is generated by forces caused by the non-uniform steady flow fields, by turbulence and turbulent flow interactions with the rigid structure, along with the flow through the fan and the electric motor. The non-rotational noise is a result of fluctuating and unstable forces; it depends on the flow velocity, the pipes shape, size and roughness inside the vacuum cleaner and the electric motor.

The mechanical rotational noise is mainly generated within the electric motor and caused by mechanical friction of the brushes on the collector, by friction of ball bearings and vibration caused by unbalanced rotating masses. The frequency of the noise generated by the brushes is given by the equation $f_{CB} = z_{CS} \cdot n$ (z_{CS} is the segments number). The ball bearings also generate discrete frequencies noise, corresponding to the rotational frequency of the elements within the bearings (shaft, balls, cage). The noise magnitude depends on the rotating speed, the manufacturing technology and precision, the materials, etc. Mechanical non-rotational noise is due to internal forces and it is intensified at higher rotation speeds, so rotating stall causes intensive fluctuation of the air flow with an increase of vibrations.

Rotational electromagnetic noise is a result of periodic fluctuations in the magnetic flux between the rotor and stator of the electric motor, which generates periodic forces. A great number of discrete noise frequencies is created; the most important are at the frequency given by the equation $f_{EM} = z_s \cdot n$ (z_s is the number of stator slots, n is the rotating speed). The non-rotational noise is derived by magnetic forces due to fluctuations of the magnetic field that cause the vibration of the electric motor parts so a broadband noise is created and it isn't related to the rotational frequency. The noise generated in the suction unit is transmitted to the entire vacuum cleaner by the surrounding air and the vibrations of the structure⁵.

2. Vacuum cleaner general characteristics

The wet vacuum cleaner is able to suck up dust, steam and liquids; an internal electric boiler can produce steam with a 500 kPa pressure to improve the cleaning efficiency. The suction unit consists of a driving electric motor (AC, 230 V, 50 Hz) and a fan impeller that produce a suitable pressure rise and flow rate to suck dust particles from the floor and pass by vacuum cleaner filters.

The electric motor maximum power is 1200 W and it can operate in 4 different rotating speeds. There are two different impellers clamped to the rotational shaft. The first one has 9 blades and produces the pressure rise; the second one has 18 blades, is located to the bottom side of the main impeller and is smaller than the first one. It's used for the motor's cooling (figure 2). The electric motor has 24 segments, provides 54 l/s air flow and a maximum head of 2400 mm H₂O.

The air enter the cleaning device by the suction handle unit related to the floor brushes and the flow reach the filters elements passing through a flexible pipe. The dirty air enter inside the device and is filtered by four different series filters (figure 2): the first one is a water filter, then there are a steel and a polyester filter. The air pass through the fan vaned diffuser and exit the device by passing a small HEPA (High Efficiency Particulate Air) filter.

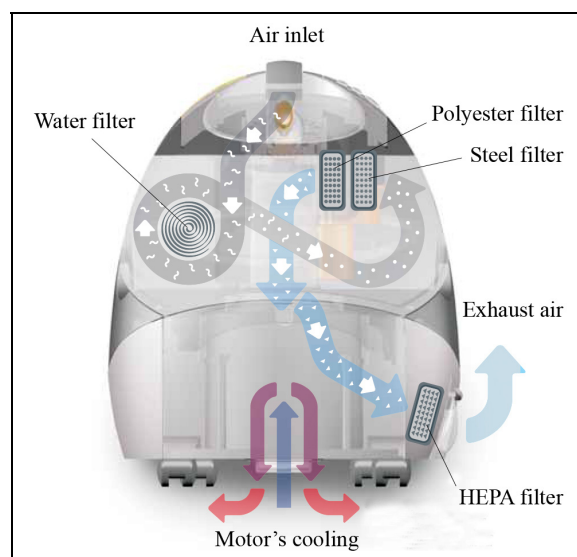


Figure 2. Air flow path in vacuum cleaner.

3. Acoustic characterization

The noise characterization was performed on the vacuum cleaner working in 4 different rotating speeds and in some configurations to assess the contribution of individual parts making up the device. For each configuration the equivalent sound level emitted and one-third octave bands spectra in the 20Hz-20kHz range according with the UNI EN 3744 standard were measured.

The sound power level was determined by using sound pressure in 10 microphone positions on a virtual hemisphere around the device in an essentially free field over a reflecting plane in compliance with UNI EN ISO 3744⁸.

Results (Figure 3) show that the emitted power levels are proportional to the rotational speeds; the effect of the electric motor is visible for the rotating speeds v_1 , v_2 and v_3 , where a sound power peak can be identified for the frequencies respectively equal to 200, 315 and 400 Hz.

This phenomenon is not detectable in the speed v_4 because the peak is covered by an increasing aerodynamic non-rotational noise emitted by the vacuum cleaner. In order to identify the noise contributions due to various parts of the vacuum cleaner, different configurations were studied, starting from the centrifugal fan up to the complete configuration. Table 1 shows the most acoustically significant configurations.

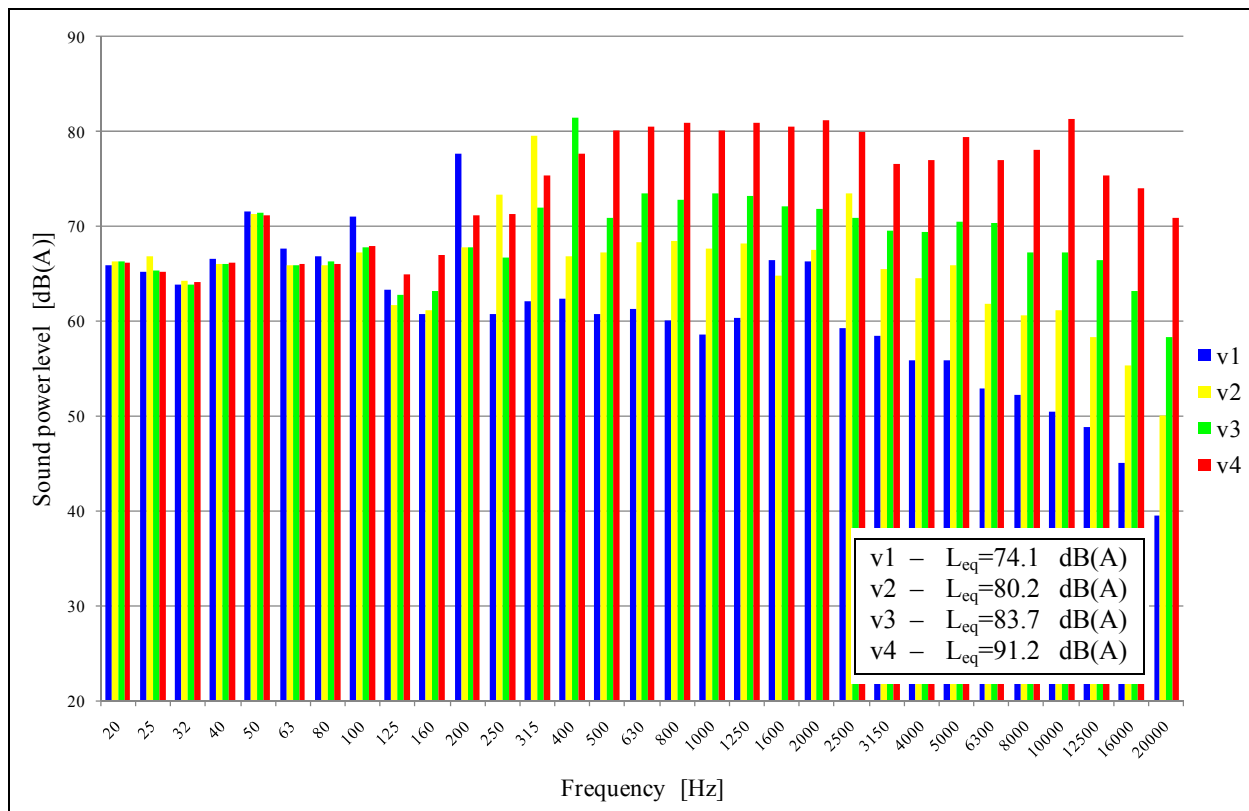








Figure 3. Sound power levels in different rotating speeds.

Table 1. Vacuum cleaner configurations in which the sound spectra was measured.

<i>Reference number and description</i>	<i>Picture</i>	<i>Reference number and description</i>	<i>Picture</i>
C1 Centrifugal fan (with electric motor)		C4 Centrifugal fan, housing, plastic cover, steam generator and full (filter) water tank	
C2 Centrifugal fan and housing		C5 Complete configuration without aspiration pipe	
C3 Centrifugal fan, housing and plastic cover		C6 Complete configuration	

Experimental tests were carried out in compliance to UNI EN ISO 3744⁸. Sound emission spectra and equivalent power level are shown in Figure 4.

The aspiration unit (C1) is the main noise source, according to the theoretical hypothesis; the spectrum shows a low noise emission in the low-middle range frequencies due to the absence of air pipe. Emitted noises are mainly due to the mechanical and electromagnetic effects; a clear power peak is identified at 5000 Hz.

In the other C2-C6 configurations, two different effects are visible: a gradual noise reduction in the medium-high range frequencies, generated by the centrifugal fan, and an increase of noise in the medium frequency range. The first effect is due to the plastic cover layers, that create a noise screen around the electric motor; they also made all the air flow path so that the fluids increase their speeds and create aerodynamic and structural noise. The point of operating of the centrifugal fan depends on the fan and system characteristic curve; an increase of the geometry complexity due to the presence of the internal pipes causes a reduction of the electric motor rotating speed. Air mass flow decrease, with a consequence loss of total noise and effective suction power.

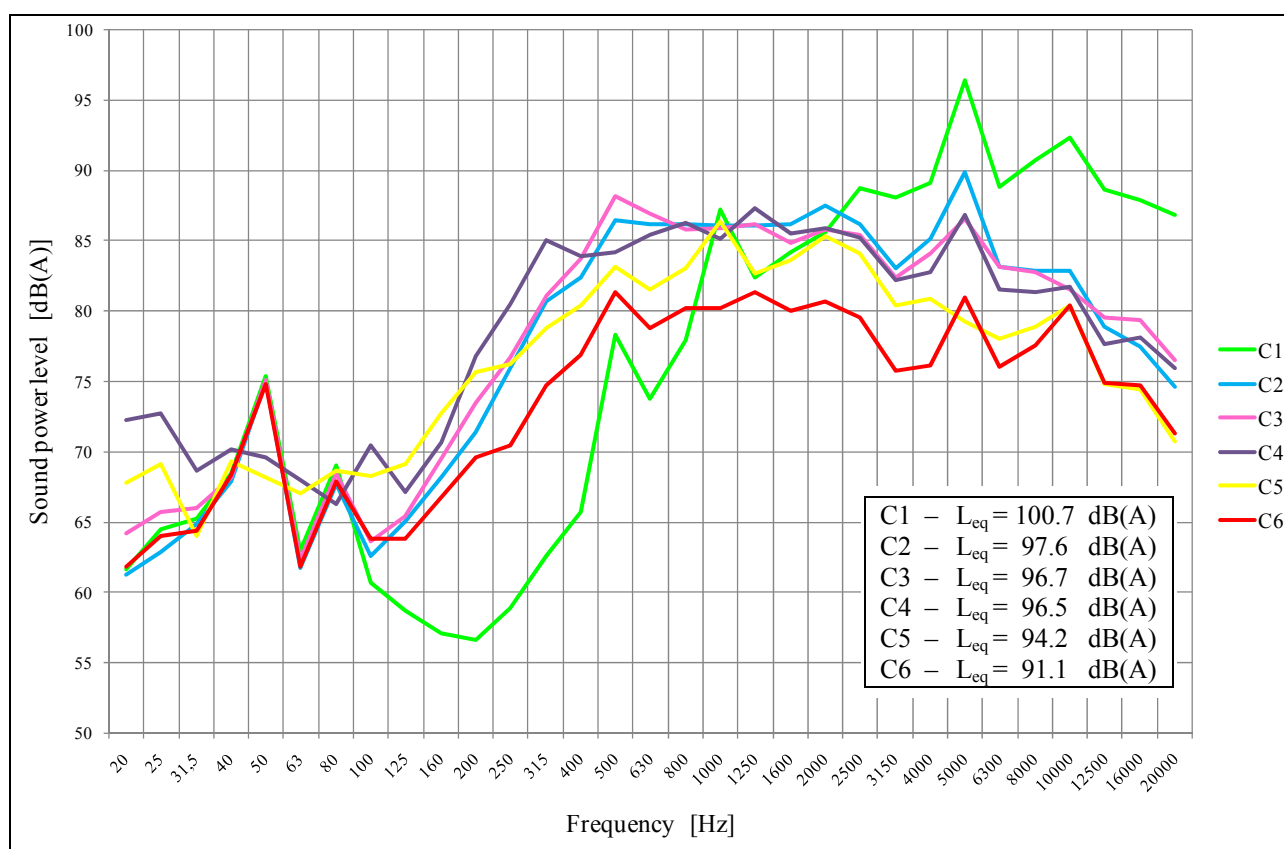


Figure 4. Sound power levels in the different vacuum cleaner configurations.

4. Narrow band analysis

A narrow band analysis was carried out to individuate the discrete tones of the noise generated by the electric motor and the vacuum cleaner. It was investigated the sound emission of the centrifugal fan (C1) and the complete apparatus (C6) in the audible frequency range with 6.25 Hz width band; results are shown in figure 5.

Centrifugal fan was firstly analyzed, in order to evaluate discrete tonal noise with mechanical origin; electric motor rotation speed is 32250 rpm ($f = 537.5$ Hz), so centrifugal fan RF and its superior harmonics are observed at 537.5, 1075.0, 1612.5 and 2150.0 Hz. The strongest discrete tones are located at fan and electric motor cooling impellers BPF (4837.5 Hz) and its superior harmonics (9675.0, 14512.5, 19350.0 Hz).

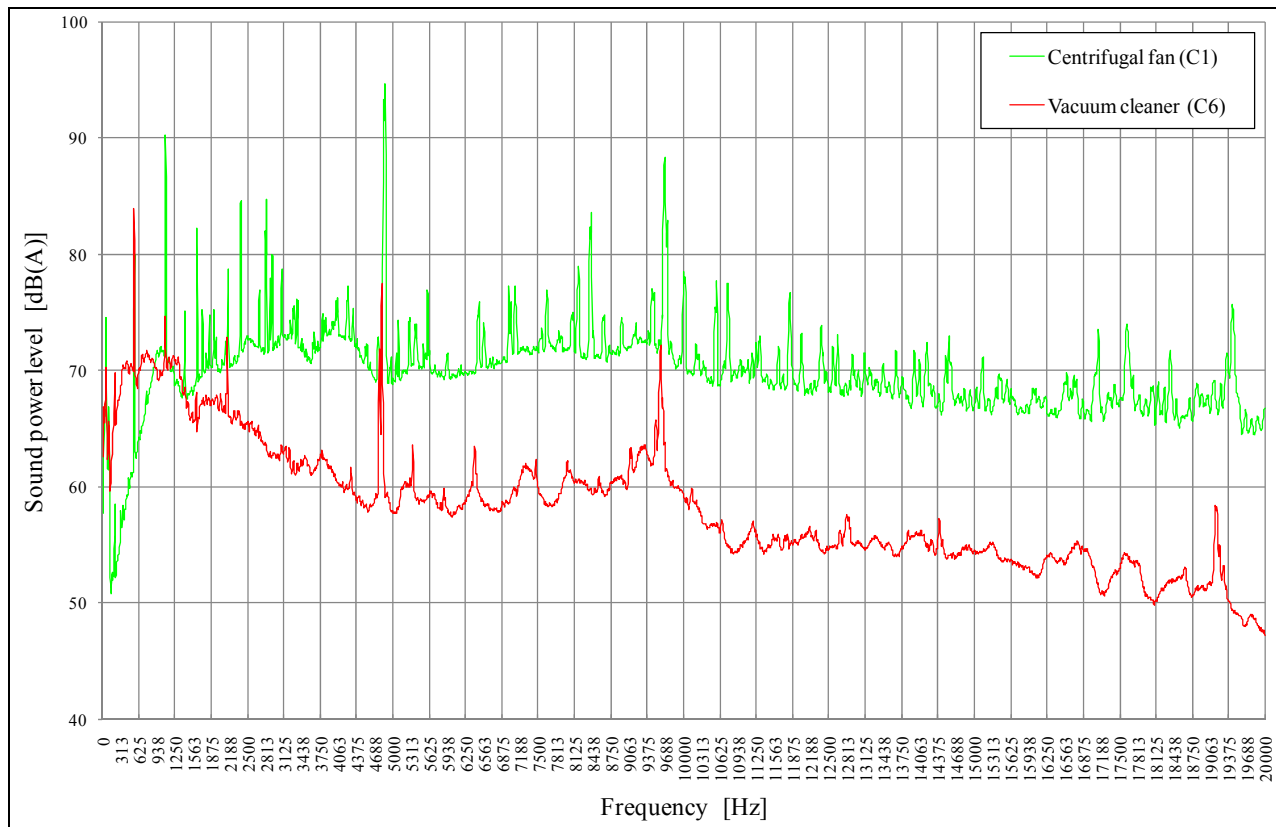


Figure 5. Centrifugal fan and vacuum cleaner narrow band analysis.

The comparison between centrifugal fan and complete device narrow-band analysis shows some sound emission differences. It can be observed an effective noise reduction of more than 10 dB, especially for frequencies higher than 10 kHz. The peaks shown in C1 configuration are partially reduced by the plastic cover. It should be noted that the presence of plastic pipes on the suction device creates an increase in terms of loss pressure and a consequent shift of the operating point. The rotating speed of the electric motor moves to 31875 rpm; the result is a *RF* and *BPF* peaks slightly left shift.

5. Noise reduction proposals

Several operations can be made on the vacuum cleaner in order to reduce noise emissions; a noise component derives from aerodynamic air flows caused by the pressure variation induced by the suction unit.

The outlet pipe of the vacuum cleaner has a shrinkage and two elbow curves (Figure 6a). This kind of geometry causes an increase of the exhaust air speed and a consequent increase in noise emissions. Therefore the pipe was modified creating a new air path without angles (Figure 6b). It was also increased the air flow area by the creation of 32 holes in the rear part of the vacuum cleaner. The area obtained increase from 9.6 to 25.1 cm² (figure 6c). A HEPA filter was placed in front of the holes (figure 6d).

Noise emissions were measured on the modified configuration. Results (Figure 7) of the comparison between and the the initial configuration (C3) and the modified one (C3_new) show a significant noise reduction in the equivalent power levels.

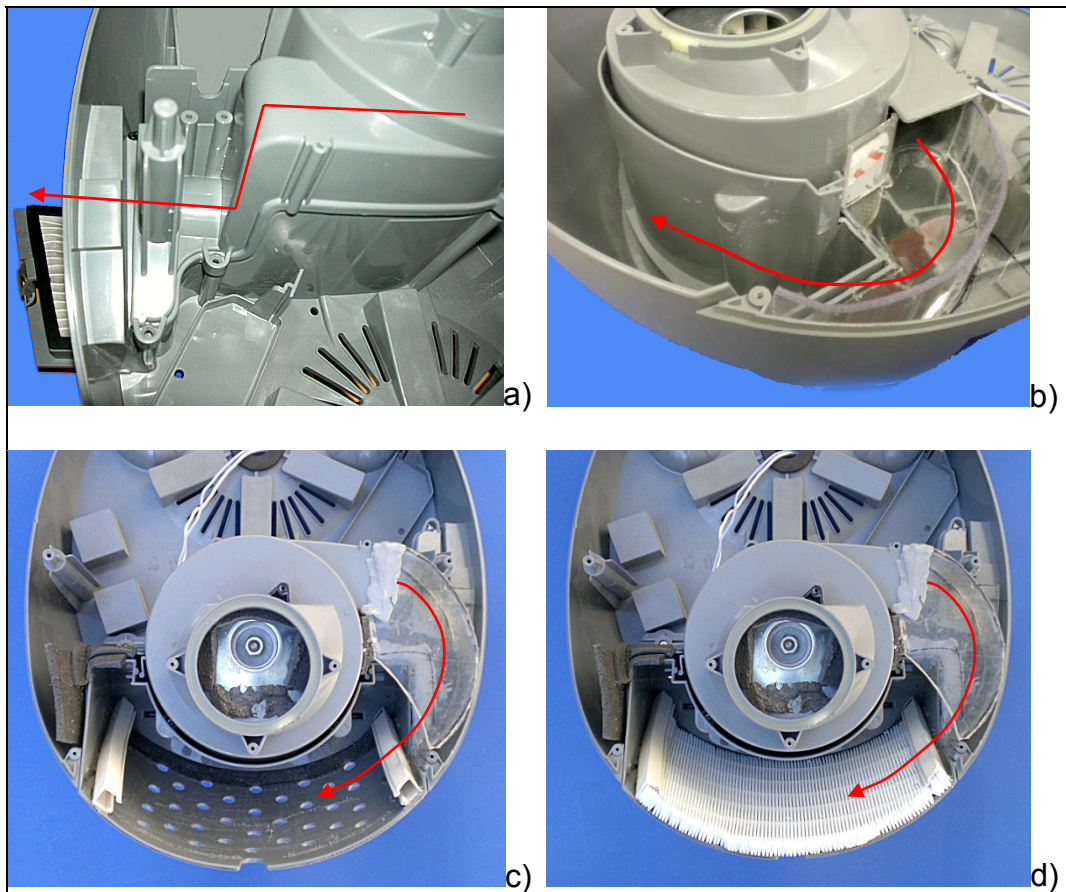


Figure 6. Exhaust air flow path (red line) before (a) and after (b, c, d) device modification.

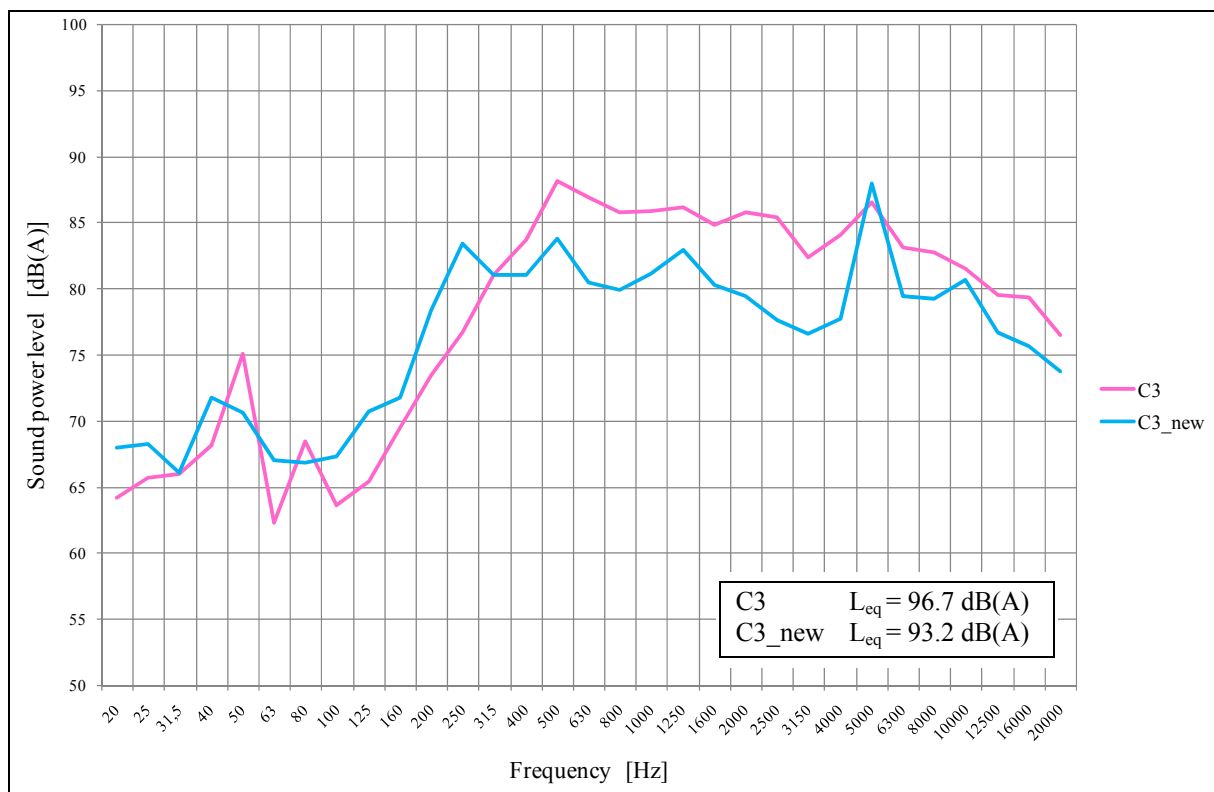


Figure 7. Sound power levels before (C3) and after (C3_new) the exhaust air flow path modification.

Experimental tests show a noise reduction in the high frequencies range, mainly due to a lower exhaust air speed.

6. Conclusion

This paper deals with an experimental acoustic characterization of a wet vacuum cleaner; the suction driving pressure is generated by a centrifugal fan and is the main cause of noise. Total emitted noise is the sum of several contributions: aerodynamic, mechanical and electromagnetic components; those components can generate discrete tone noise (rotational noise) and broadband noise (non-rotational noise).

It was firstly described the vacuum cleaner, its performances and the particular inlet and outlet air flow pathways through the aspiration unit, pipes and filters; it was evaluated the sound power level at each rotational speed allowed, in compliance with UNI EN ISO 3744 (*Determination of sound power levels of noise sources using sound pressure – Engineering method in an essentially free field over a reflecting plane*). The equivalent power level for the maximum rotating speed measured was 91.2 dB. The noise spectrum also showed high frequencies emission components, mainly due to the high air flow speed through the vacuum cleaner pipes.

It was analyzed the contribution which gradually compose the standard configuration; an emission spectra analysis allowed to distinguish the noise causes of the configurations studied. The higher equivalent power level was measured for the C1 configuration (centrifugal fan); the other configurations (from C2 to C6) showed a double effect on the global sound emission: a general reduction of noise due to the screen effect of plastic layers around the suction unit and a frequencies left shifting due to air flow path created by the plastic cover that constitute the vacuum cleaner were observed.

In order to individuate discrete tonal noise it was performed a narrow band analysis; rotational shaft and blade and passing frequencies (with superior harmonics) were identified at 537.7, 1075.0, 1612.5 and 2150.0 Hz for the C1 configuration, according with the Literature^{1,5}.

An outlet pipe path modification was realized to remove elbow angles and increase the section exhaust air area; experimental tests showed a 3.5 dB noise reduction.

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