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SOUND QUALITY AND LOW NOISE DESIGN: AN APPLICATION ON VACUUM CLEANERS

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ABSTRACT
The noise radiated from the household appliances is a serious problem in our daily life. Wet and dry type vacuum cleaners are among the noisiest household appliances. The reduction of the vacuum cleaner noise has become a main concern of manufacturers in order to comply with the European Union Directives. Major parameters of vacuum cleaner design are sound power level, sound quality and efficiency. Vacuum cleaners should be designed with minimal disturbing sound without reducing their efficiency. The aim of this investigation is twofold; firstly, to describe a noise control study that resulted in 8 dB (A) reduction in sound power level at a moderately low cost with an efficiency reduction of only 2 %; secondly, to propose a set of design principles for improved sound quality and low noise design for vacuum cleaners based on the experience obtained in this study.

1 - INTRODUCTION
Growing emphasize in reducing the product sound levels in addition to improving the product sound quality makes it essential for designers to consider design procedures as early as at the concept development stage. Once the product is designed and the production is started, the costs involved in improving the sound quality of the product becomes considerably higher.
Kuwano et al [1] conducted jury tests for various household appliances and described three classes; namely, actual, ideal and intolerable. Jury members when asked how much they were prepared to spend to improve the actual sound level to ideal sound level, replied that they were prepared to spend between $68-75$ USD on vacuum cleaners. Also more than half of the jury members indicated that they wanted noise reduction and control on vacuum cleaners.
Wet and dry type vacuum cleaners are among the noisiest household appliances and therefore their sound quality has high correlation with their sound power level. In addition, reduction of the vacuum cleaner noise has become a main concern of manufacturers in order to comply with European Union Directives. Sarbu and Kraft [2] used sound intensity techniques to identify the noise sources and reduced the sound power level on a dry type vacuum cleaner. Altinsoy et al [3] introduced two annoyance indexes for the wet-and-dry type vacuum cleaner noise based on a comparative study conducted on similar vacuum cleaners of six different trademarks. They provided to the vacuum cleaner manufacturers two useful scalar indexes. These indexes were function of metric values and enabled the designer to assess the relative merit of his product‘s sound quality without conducting extensive jury tests at the design stage. While one of the major parameters of the vacuum cleaner design is its sound, another major parameter is its efficiency. Vacuum cleaners should be designed so as to produce as little disturbing sound as possible without reducing their efficiency.
The main purpose of this investigation is twofold. Firstly, to describe a noise control study that resulted in 8 dB (A) reduction in sound power level at a moderately low cost with an efficiency reduction of only

2 %. Secondly, a set of design principles for improved sound quality and low noise design for vacuum cleaners will be proposed based on the experience obtained in this study.

2 - NOISE CONTROL ANALYSIS

The tested vacuum cleaner was already designed and the production was about to begin when the project started. Therefore the aim was to improve the sound quality and reduce the sound power on the existing design with minimal cost. A picture of the wet-and-dry type vacuum cleaner is given in Figure 1.

Figure 1: A view of the wet-and-dry type vacuum cleaner.

The noise control study consisted of four stages:

- Source identification and source ranking by the sound intensity measurements,
- Investigation of the structural noise generation mechanism by the near field sound pressure and vibration measurements,
- Application of appropriate noise control methods by selection of sound and vibration isolation materials and by designing an appropriate exhaust silencer,
- Finally, assessments of the results of the noise control study together with the evaluation of product sound quality and providing feedback for further modifications.

To identify and evaluate the noise sources of the vacuum cleaner, the sound pressure and the sound intensity measurements were made in a semi-anechoic room with a volume of 144 m^3. Sound intensity measurements were made with Brüel & Kjaer Type 3548 intensity probe and Brüel & Kjaer Type 2144 real-time dual-channel frequency analyzer. In accordance with ISO 9614-1: 1993, the vacuum cleaner was placed on the special carpet covered 1 ×1 square meter floor in a 1 ×1 ×1 m cube grid with hose and water tank connected and set to operate under normal working conditions. The grid elements are formed by 25 ×25 cm squares. The overall intensity magnitude is measured in the frequency range of 200 Hz to 8 kHz and the sound intensity mappings of vacuum cleaner are obtained by using Brüel &

Kjaer 7681 Noise Source Location Software. Sound power values for the source ranking are shown in Fig. 2 and the intensity mapping on the rear side indicates high intensity values around the exhaust area Fig. 3.

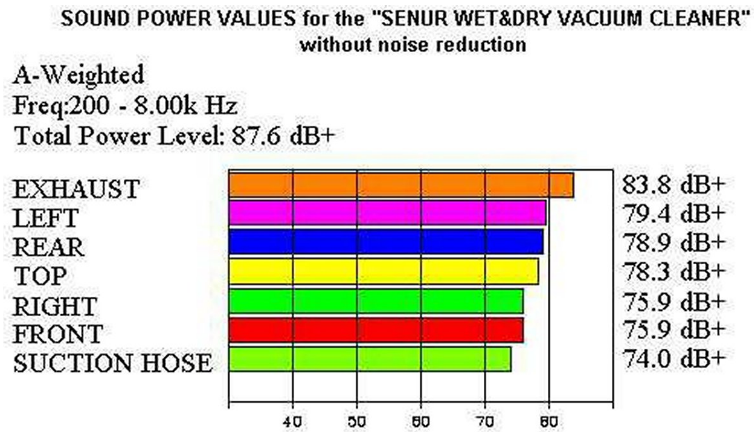

Figure 2: Sound power values for the source ranking.

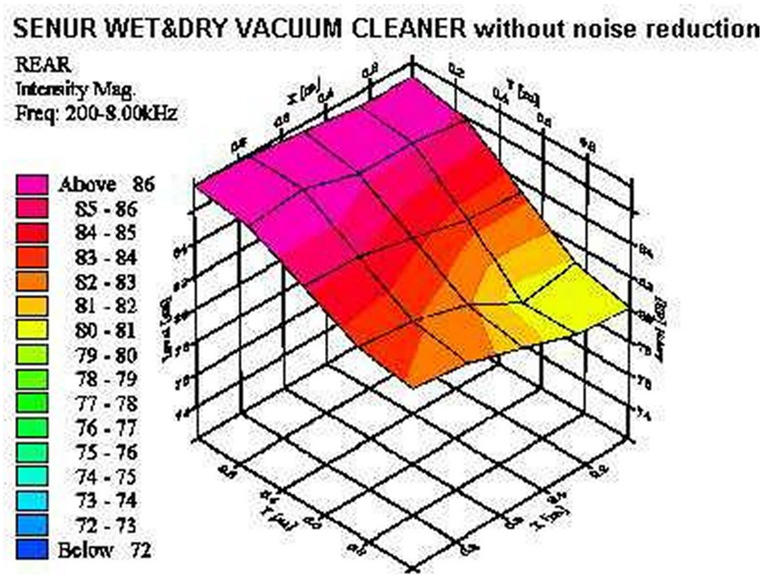

Figure 3: Sound intensity mapping for the rear side of the vacuum cleaner.

The sources of noise in a vacuum cleaner can be classified as; electrical motor noise, structure borne noise and air borne noise. These sources and their frequency characteristics are summarized in Table 1. A more detailed account of noise sources particularly in the electrical motor fan units can be found in reference [4]. In the present study, the possibility of making modification on the electrical motor-fan systems was limited. The only measure taken was the reduction of residual unbalance on the production line.

With this information in hand along with the limitations imposed by the ongoing production, a number of modifications were planned and applied. They are listed below:

- An exhaust silencer with internal porous lining was designed and fitted on the rear exhaust port. Porosity of the lining was optimized giving minimum pressure drop across the silencer.
- Softer rubber seals were introduced to minimize the vibration transmission.
- Appropriate composite materials with sound barrier and absorption characteristics for better sound isolation were applied around the fan cover where maximum air velocities were reached.
- Sound quality parameters were evaluated and compared with other manufacturers units.

Noise Source	**Frequency Component**
Electrical Motor, Electromagnetic and mechanical noise sources	Rotating Speed and its harmonics; Rotating speed × Number of Grooves in the collector or Number of Slots in the Rotor
Suction Fan Aerodynamic noise	Rotating Speed × Number of fan blades; Generally broad band
Air Flow through passages	Broad band noise
Structural Vibrations	Rotating speed and depending on the resonance of various parts discrete frequencies

Table 1: Noise sources in the wet-and-dry-type vacuum cleaner.

Based on these modifications substantial reduction in the sound power was achieved. The results are summarized in Table 2.

Noise control study results	**Sound power level**
Vacuum cleaner without noise reduction	88.2
Vacuum cleaner fitted with appropriate composite material barrier and exhaust silencer	83.3
Vacuum cleaner with soft rubber isolators and a silencer	83.7
Vacuum cleaner with appropriate composite material, soft rubber isolators, and silencer	80.1

Table 2: Sound power levels after the noise control application.

Finally, 1/3 Octave Band Average Sound Pressure Level, FFT Averaged Spectrum, Fluctuation Strength, Loudness Stationary Spectrum and Roughness Values were calculated using Brüel & Kjaer Type 7698 Sound Quality Software. The results are displayed in Figure 4. The summary of Sound Quality Metric values are given in Table 3 for the vacuum cleaner with and without noise control measures applied respectively.

Metrics	Zwicker Loudness [Sone]	Sharpness (Aures) [Acum]	Roughness [Asper]	Fluctuation Strength [Vacil]	Tone-to-Noise Ratio	Prominence Ratio
Without SQ & NC	29.1	4.94	0.407	1.27	27.4	23.7
With SQ & NC	17.6	4.31	0.511	1.89	13.3	7.16

Table 3: The summary of Sound Quality Metrics without and with sound quality and noise control applied.

3 - DISCUSSIONS & CONCLUSIONS

Noise control principles were successfully applied and sound power level of the wet-and-dry type vacuum cleaner was decreased around 8 dB (A) along with substantial improvement in the product sound quality. Based on the work performed a set of design principles will be recommended to obtain better sound quality and lower sound power levels for the vacuum cleaners in general.

- Insert the motor-fan in a sealed housing by using soft rubber seals. Between the housing and the vacuum cleaner body use soft rubber pads to minimize the transmission of structure borne vibrations into the casing.
- Minimize the external vacuum cleaner surface area to decrease the propagation of noise in the air through surface vibrations.
- Make the outer shell of the casing as rigid as possible to reduce the structure borne noise via surface vibrations. Ideally an egg shaped outer structure will have a higher rigidity with minimum area.
- Use of labyrinth type of passages for air circulation with appropriate liners on the passage surfaces with acoustical energy absorption, while ensuring minimal pressure drop.

- Use appropriate composite materials with sound barrier and absorption characteristics for better sound isolation.
- Higher the speed of the motor and lower the residual unbalance.
- Use as many blades as your design would allow on your fan to achieve higher fan characteristic speed.

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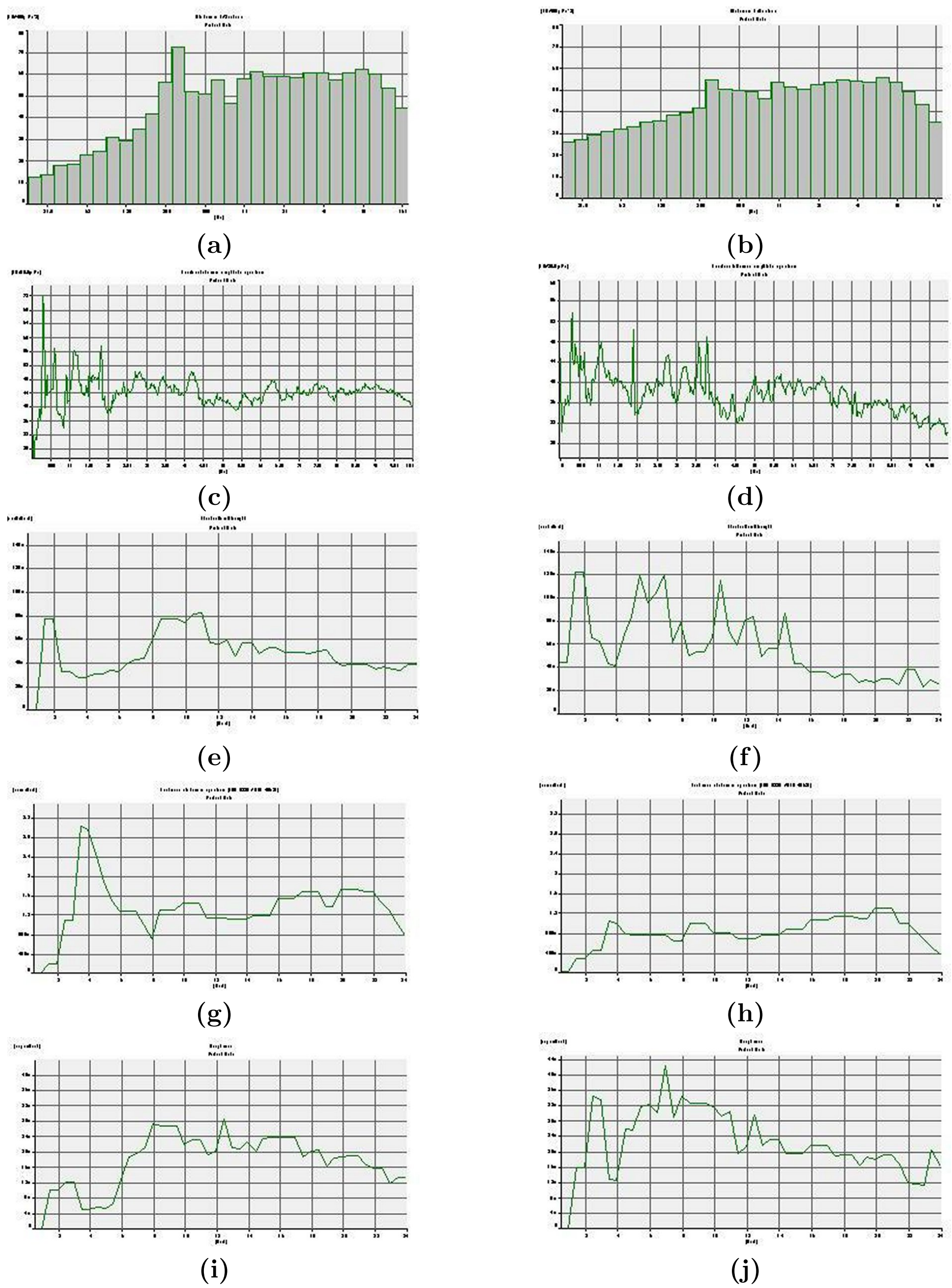

Figure 4: 1/3 Octave Band Average Sound Pressure Level, FFT Averaged Spectrum, Fluctuation Strength, Loudness Stationary Spectrum and Roughness Values for the two cases.