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MODIFICATIONS OF A VACUUM CLEANER FOR NOISE CONTROL

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ABSTRACT
Sound power measurements are described for a commercially manufactured, hand-held vacuum cleaner. Both objective and subjective assessments of the measured results are performed. The aeroacoustic sources of noise are identified and routes to noise control are implemented. A reevaluation of the modified units is conducted and results are compared to the baseline results. The blade rate tone of the vacuum working fan is found to be the most annoying source, and it is reduced by up to 8 dB through a modification of the shroud that surrounds it. Unevenly spaced fan blades are also implemented as a noise control measure. This results in a comparable 8 dB reduction of the blade rate tone, but it introduces several new, side band tones to the sound power spectral data; the overall sound power increases slightly. Regardless, a subjective jury survey indicated preference to this unit.

1 - INTRODUCTION

A vacuum cleaner is an air-moving device that can generate excessive noise levels due to many separate but oftentimes interacting, noise generating mechanisms. Induction motors can be annoying acoustically because of brush arcing, rotor-stator interactions, tones created by cooling fans, bearings, and rotor imbalance. The vacuum working fan can create noise by numerous mechanisms including inflow distortions and turbulence, impeller-shroud interactions, impeller-particle interactions, and stalled impeller blades due to excessive aerodynamic loading. As a system, the fan and motor can couple with supporting structures to cause mechanical and flow-induced vibrations of the housing, which, in some instances, radiates acoustical energy.

It is desirable to incorporate noise and flow control measures into certain present and future vacuum cleaner designs. Earlier work [1] focused on identifying the most dominant noise generating features of an upright vacuum cleaner and demonstrating noise control measures that would result in no degradation in performance or increase in production costs. In that work it was found that aerodynamic sources dominated the vacuum cleaner's radiated noise. More specifically, aerodynamic interactions occurring between the electric motor cooling fan and nearby motor mounting fixtures resulted in intense tones at blade rate and harmonic frequencies. These tones were reduced up to 25 dB in level, to the broadband sound power level of the unit, by eliminating certain flow obstructions, and mounting the motor in an alternative fashion.

The current work focuses on identifying the dominant noise generating features of a small handheld vacuum cleaner.

2 - BASELINE RESULTS

The noise emitted from the vacuum cleaner of interest, as well as the effect of the noise control modifications performed, is quantified in terms of sound power. Sound power and its measurement are described in detail in [1]. The same techniques and equipment, based on ISO specification 7779, are used in the subject investigation. A vacuum cleaner operates under a variety of flow conditions ranging from free-delivery to stall. Free-delivery conditions are achieved by allowing the flow to pass into the vacuum working fan (VWF) uninhibited. Stalled conditions are achieved by choking the airflow to the VWF. The sound power radiated by the vacuum cleaner at both free-delivery and stalled flow conditions is shown in Figure 1. In general, the tone at the blade rate frequency of the 6-bladed vacuum working fan (1xVWF BR) is the most prominent feature in the two spectra. This tone also tends to be the most annoying component of the sound radiated from the unit. At the stalled flow condition the electric motor speed increases and as a result, the frequency of the acoustic line components associated with the VWF and the electric motor cooling fan (EMCF) increase. In order to identify the relative contribution of motor-induced and aerodynamic noise sources to the sound power radiated by the baseline unit, it was operated without its VWF.

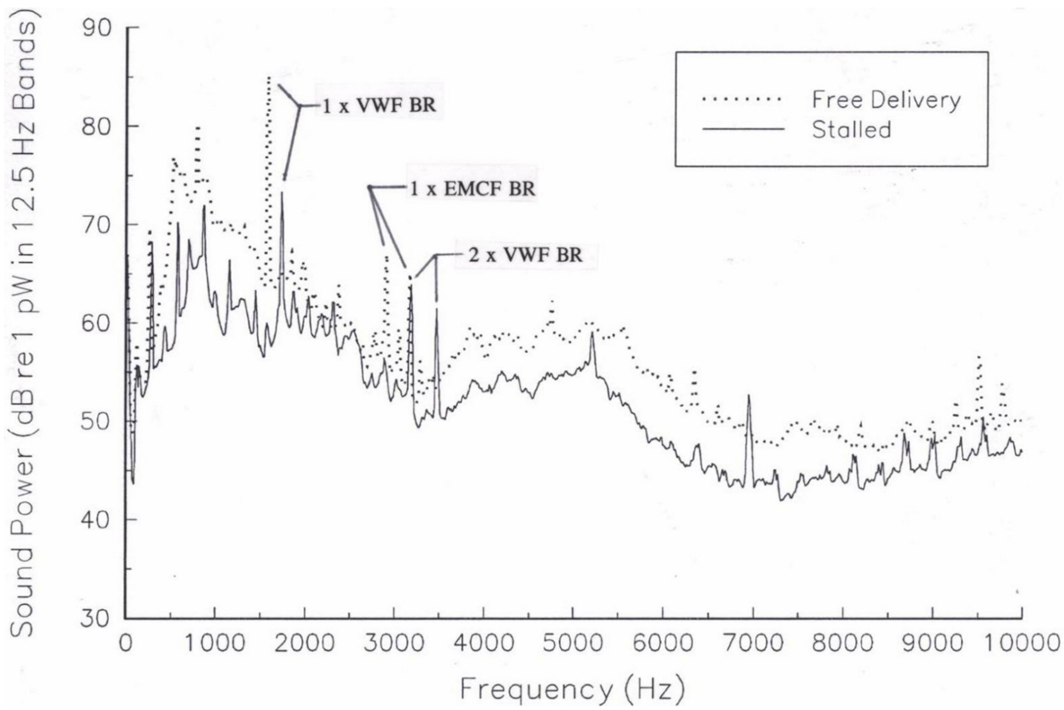

Figure 1: Sound power of the vacuum cleaner under stalled and free-delivery conditions.

Figure 2 compares the sound power radiated by the baseline vacuum cleaner operating under free-delivery flow conditions to the same unit operating without its VWF at the free-delivery shaft rate (SR) of 1578 RPM. The data indicate that the greatest electric motor contribution to the radiated sound is from 1.5 to 3.5 kHz, where the first blade rate harmonic of the EMCF occurs. The aerodynamic sources due to the VWF are dominant at higher and lower frequencies.

3 - NOISE CONTROL MODIFICATIONS

The noise control modifications performed on the handheld vacuum cleaner focused on reducing the annoyance due to the 1xVWF BR tone. Two approaches were used: 1) modify the VWF shroud (stone shield), and 2) introduce additional tones into the noise spectrum as to "whiten" the sound. People tend to perceive whitened sound as much less annoying than discrete frequency noise. This was accomplished by utilizing a VWF with unequal blade spacing. The tone at the blade rate frequency of the VWF is produced by an interaction between the VWF and its volute; commonly referred to as the stone shield. The pressure fluctuations resulting from passage of the VWF blades past inside corners of the shield can be reduced by appropriately filling-in and reshaping these corners. A photograph of this modification, performed with clay, is shown in Figure 3 along with a photograph of a baseline stone shield for comparison. A 6-bladed vacuum working fan with unevenly spaced blades was NC machined from a block of acetal plastic. The blades of this fan are geometrically identical to those of the baseline, but are unevenly spaced circumferentially in the dynamically balanced configuration specified by Mellin and Sovran [2]... The modified fan is shown with respect to its evenly spaced counterpart in Figure 4.
Figure 5 compares the sound power spectra of the baseline vacuum cleaner to that of the unit modified with the unevenly spaced 6 bladed VWF operating within the modified stone shield. As expected, these

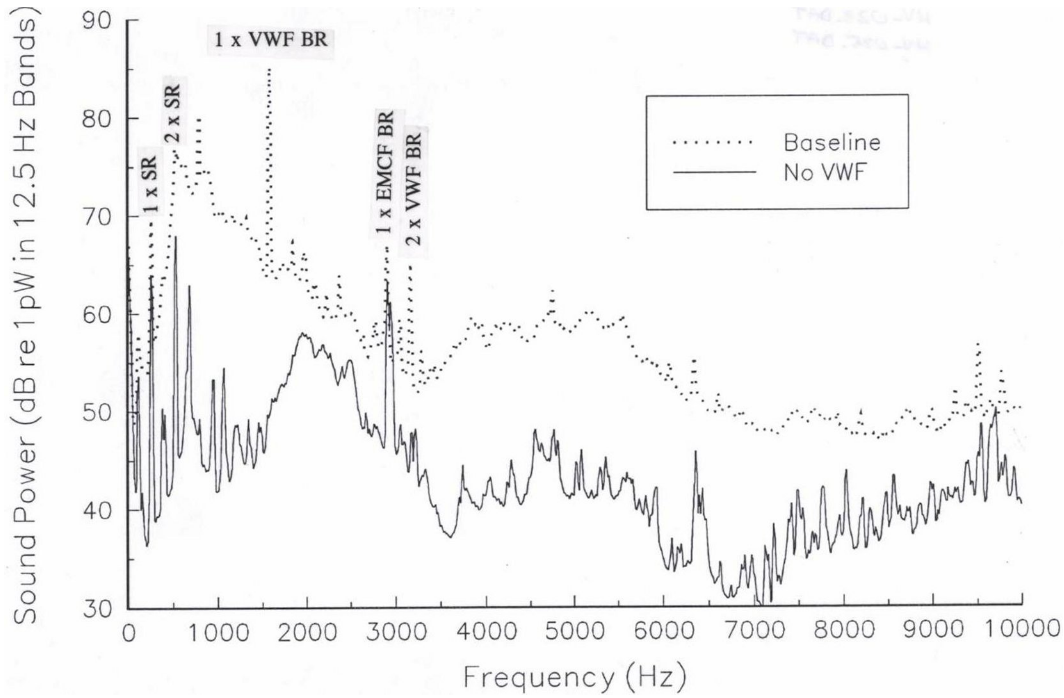

Figure 2: Sound power of vacuum cleaner with and without the vacuum working fan in operation.

modifications generate numerous tones at harmonics of the shaft rate frequency, but the results do not provide a direct measure of how people perceive the sound from the modified unit.

4 - JURY EVALUATION

Lions [3] points out that sound quality is product specific and the usual psychoacoustic metrics used to interpret the sound quality may not be the scale the customer is using. Therefore, the most effective means of quantifying annoyance and the preference of one sound over another, such as the sound from a vacuum cleaner, appears to be through subjective jury testing. Two modified vacuum cleaners and one baseline unit were selected for jury evaluation. Modified unit No. 1 (Mod #1) consisted of the baseline VWF operating within the modified stone shield shown in Figure 3. Modified unit No. 2 (Mod #2) consisted of the unevenly spaced 6 bladed VWF shown in Figure 4 operating within the modified shield. Thirty-three men and seven women were selected at random to form a jury. The subjects ranged in age from approximately 19 to 62 years and not all had acute hearing. The testing took place in a small, carpeted conference room containing a table and several chairs. The same examiner administered the survey to each subject on an individual basis. All three handheld vacuum cleaners were positioned on the table and the subject faced the table and was instructed to grasp the baseline unit, turn it on and listen to it, and then do likewise to Mod #1 and in turn to Mod #2. After this initial direction the subject was instructed to compare the units at his/her own discretion. The specific questions asked each subject are summarized in Table 1 and the results from the survey are summarized in Table 2. The data clearly indicate a strong preference for the sound produced by Mod #2 even though the overall sound power produced by this machine is some 6 dB greater than that of the baseline unit.

1.	Which vacuum cleaner sounds most annoying?
2.	Which vacuum cleaner sounds least annoying?
3.	Which vacuum cleaner sounds most powerful?
4.	Which vacuum cleaner sounds least powerful?
5.	Which vacuum cleaner would you buy?
6.	Would sound affect your decision of which unit to buy?

Table 1: Questions asked in the jury survey.

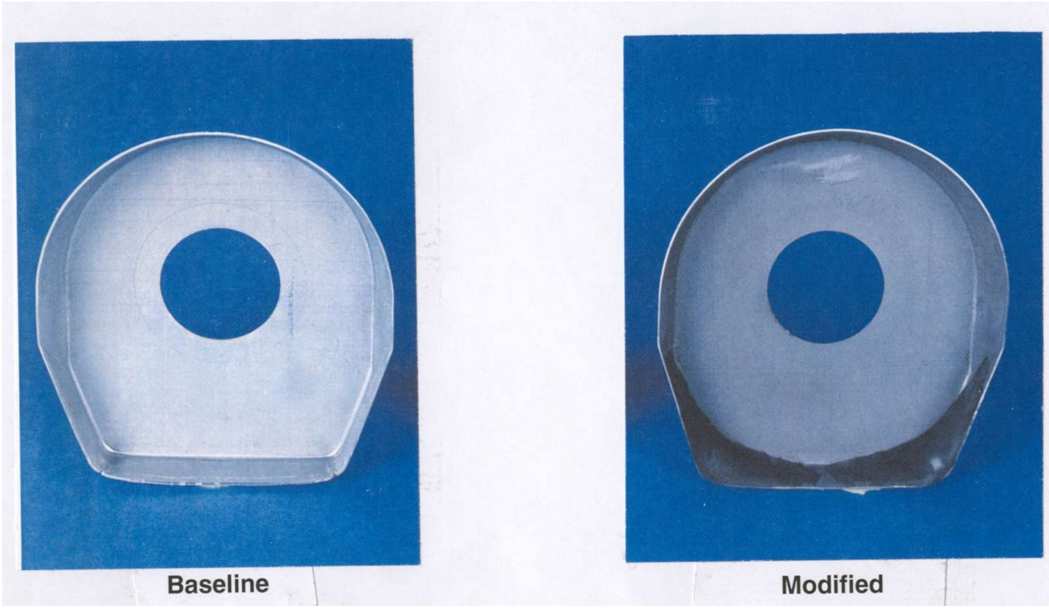

Figure 3: Comparison of the modified stone shield with the baseline.

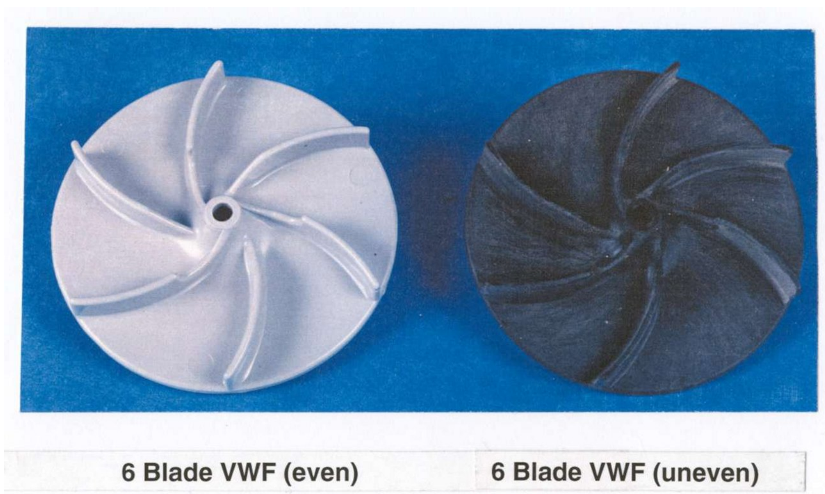

Figure 4: Comparison of the baseline VWF with the one with unequal blade spacing.

Rating	***Baseline (%/# votes)***	***Mod. #1 (%/# votes)***	***Mod. #2 (%/# votes)***
Least Annoying	17.5% (7/40)	30.0% (12/40)	52.5% (21/40)
	25.0% (10/40)	60.0% (24/40)	15.0% (6/40)
Most Annoying	57.5% (23/40)	10.0% (4/40)	32.5% (13/40)
Most Powerful	27.5% (11/40)	40.0% (16/40)	32.5% (13/40)
	45.0% (18/40)	42.5% (17/40)	12.5% (5/40)
Least Powerful	27.5% (11/40)	17.5% (7/40)	55.0% (22/40)
Would Purchase (based upon the sound)	17.5% (7/40)	30.0% (12/40)	52.5% (21/40)

Table 2: Results from the jury survey.

5 - SUMMARY AND CONCLUSIONS

Sound power measurements were performed on both baseline and modified handheld vacuum cleaners in order to identify those features responsible for generating noise. Aerodynamic sources were found to dominate the radiated noise and the tone at the blade passage frequency of the vacuum working fan was

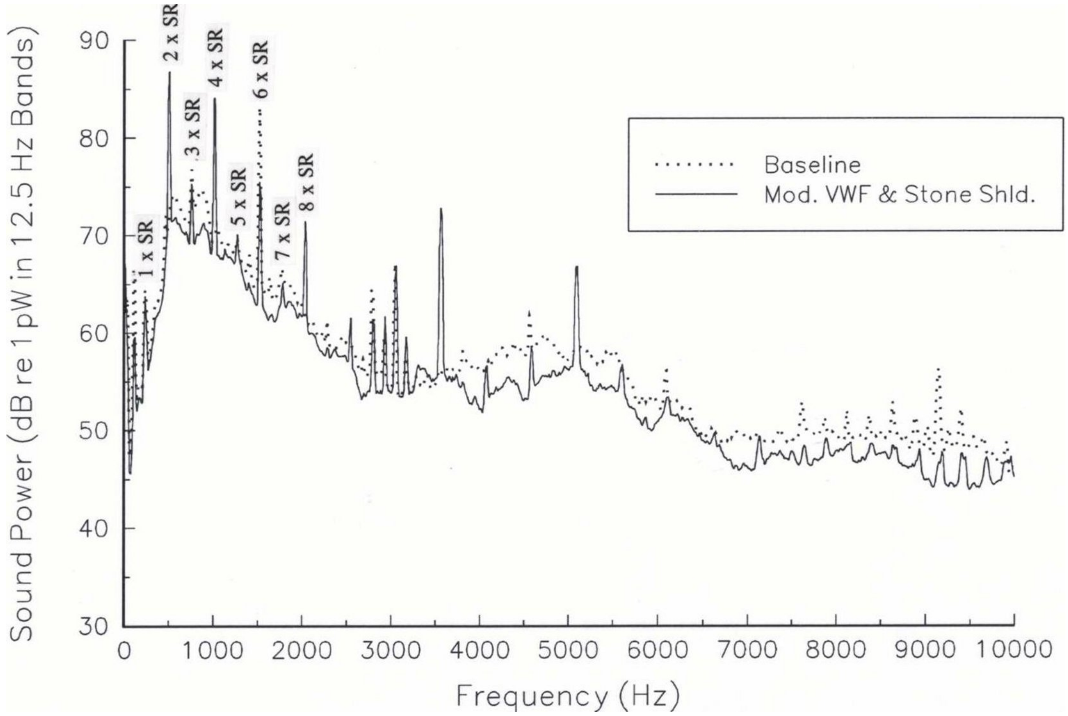

Figure 5: Comparison of sound power of baseline and modified units.

identified as the most annoying component of the radiated sound. Noise control modifications focused on either reducing the strength of the 1xVWF BR tone and/or introducing additional tones designed to effectively mask the BR tone. Appropriately filling-in and reshaping of the corners of the stone shield reduced the 1xVWF BR tone level by up to 8 dB. Additional tones were introduced at harmonics of the shaft rate frequency through an unevenly spaced 6 bladed VWF used in conjunction with stone shield modifications. The effectiveness of reducing the annoyance of the sound radiated by the vacuum cleaner with various modifications was quantified through jury testing. The jury survey clearly indicated a general dislike for the baseline tone-dominated unit through a 3 to 1 preference for the unit equipped with the unevenly spaced 6 bladed VWF and stone shield modification (Mod #2). The overall loudness level of this unit is actually higher than the annoying baseline unit by 6 dB.

ACKNOWLEDGEMENTS

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