Modifications of a handheld vacuum cleaner for noise control

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Sound power measurements were performed on a handheld vacuum cleaner in order to identify predominant noise generating mechanisms and recommend corrective noise control modifications that would result in no increase in production costs. These modifications were then implemented and their effectiveness quantified. The noise radiated by the vacuum cleaner was found to be dominated by aerodynamic sources with the tone at the blade passing frequency (BPF) of the vacuum working fan being the most annoying component. Modifications to the fan casing reduced this BPF tone up to 8 dB in level. A nine bladed vacuum working fan also reduced the BPF tone level 8 dB. A vacuum working fan with unevenly spaced blades and fan shroud modifications were introduced in an attempt to mask the fan BPF tone by creating additional tones. Jury survey results showed that the vacuum cleaner modified to create additional tones was preferred 3 to 1 over the baseline unit even though the overall tone loudness level was increased by 6 dB. *© 2001 Institute of Noise Control Engineering.*

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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 (VWF) 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 (EMCF) and nearby motor mounting fixtures resulted in intense tones at the fan blade passing frequency (BPF) and its harmonics. 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[2,3] again focuses on identifying the dominant noise generating features of a vacuum cleaner and applying noise control measures. Oftentimes, a clearly dominant source of radiated noise, such as that encountered previously,[1] may not exist. In such cases, multiple noise control measures may be required to reduce radiated noise levels. Multiple noise control measures are more likely to increase system complexity and production costs. Even if a dominant noise source does exist, it still may not be practical or possible to substantially reduce its level due to these constraints. An alternative to reducing the noise "volume" in order to reduce acoustic annoyance is to tailor the sound spectrum in order to mask, or shift, offending components to different frequency bands. Both methods were applied to the vacuum cleaner considered in this study.

A. Vacuum cleaner description

The unit of interest is a small, handheld vacuum cleaner shown schematically in Fig. 1. Air is ingested into the cleaning head and turned 90° into the VWF. The air is expelled radially from the VWF and then again turned 90° where it proceeds to the bag through a channel in the bottom of the vacuum cleaner, located beneath the electric motor. The airflow path is depicted in Fig. 1 along with the primary vacuum cleaner components.

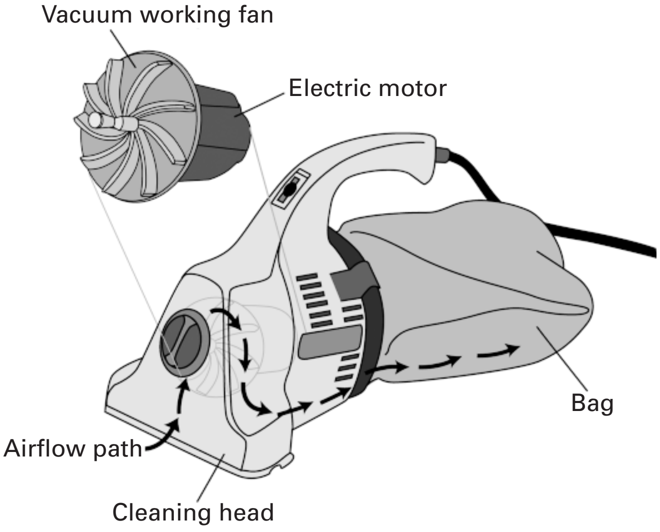

Fig. 1 – Schematic of the handheld vacuum cleaner

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2. SOUND POWER MEASUREMENT SET-UP AND PROCEDURES

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 Brungart, Lauchle, and Ramanujam.[1] The same techniques and equipment described in Ref. (1) were used to measure the sound power from the current unit. In summary, the sound power radiated from a vacuum cleaner is measured in the ARL Penn State Flow-Through Anechoic Chamber[4,5] in accordance to ANSI specification S12.34-1988. For testing, the unit was placed on a small piece of carpet located on the concrete floor of the chamber. Due to the small size and complex shape of the unit, seventeen (17) point sound pressure measurements were performed on a rectangular measurement grid surrounding the vacuum cleaner. The radiated sound power spectrum level [$L_w(f)$] is computed from

$$L_w(f) = 10\log\left(\frac{1}{N}\sum_{n=1}^{N}10^{0.1L_{pn}(f)}\right) + 10\log\left(\frac{S}{S_0}\right), \qquad (1)$$

where f is the frequency (Hz), $L_{pn}(f)$ is the sound pressure spectrum level (dB re 2×10^{-5} Pa) measured at location n, N = 17, S is the rectangular control surface area, and S_0 is the reference area of 1 m^2. The overall, A-weighted radiated sound power level (L_{WA}) is computed by A-weighting $L_{pn}(f)$ in Eq. (1) and integrating over f from 20 Hz to 10 kHz.

3. ACOUSTIC CHARACTERIZATION OF THE BASELINE UNIT

In practice, the 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 VWF uninhibited. Stalled conditions are achieved by choking the airflow to the VWF by ingesting a piece of cloth into the cleaning head. The sound power radiated by the vacuum cleaner at both free-delivery and stalled flow conditions is shown in Fig. 2. The BPF in Hz is computed from

$$BPF = \frac{(SR)B}{60}, \qquad (2)$$

where SR is the shaft speed in rotations per minute (RPM) and B is the number of fan blades. In general, the tone at the BPF of the 6-bladed vacuum working fan (1xVWF BPF) is the most prominent feature in the two spectra. With SR and B equal to 15780 RPM and 6, respectively, the BPF is 1578 Hz. The (1xVWF BPF) 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 EMCF increase. The most notable difference between the two spectra is the 8 dB reduction in L_{WA} under stalled flow conditions. The tone level at the 1xVWF BPF is reduced approximately 12 dB and the broadband sound level is reduced typically another 10 dB at low frequencies. At frequencies between 1.5 and 3.5 kHz, the broadband sound is less affected by the change in flow conditions, whereas at frequencies above 3.5 kHz, the broadband sound level is reduced 4 to 6 dB under stalled flow conditions. These data suggest that motor-induced noise may be dominant between 1.5 and 3.5 kHz but at higher and lower frequencies, the noise is aerodynamic in origin.

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 with its VWF removed at SR = 15780 RPM (corresponding to free-delivery flow conditions), and the radiated sound power was measured. The focus is on the free-delivery condition because a handheld vacuum cleaner is most often turned on when the VWF flow is unobstructed. Figure 3 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 RPM. Figure 3 confirms that the greatest electric motor contribution to the radiated sound is from 1.5 to 3.5 kHz. The aerodynamic sources of the VWF are dominant at higher and lower frequencies. Some motor-

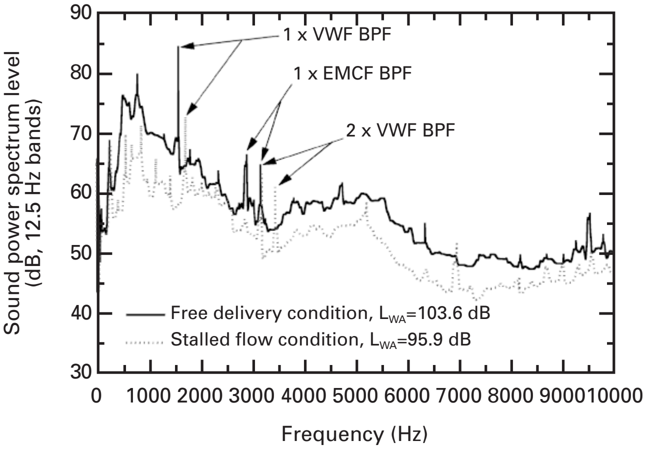


Fig. 2 – The sound power radiated by the handheld vacuum cleaner at both free-delivery and stalled flow conditions.

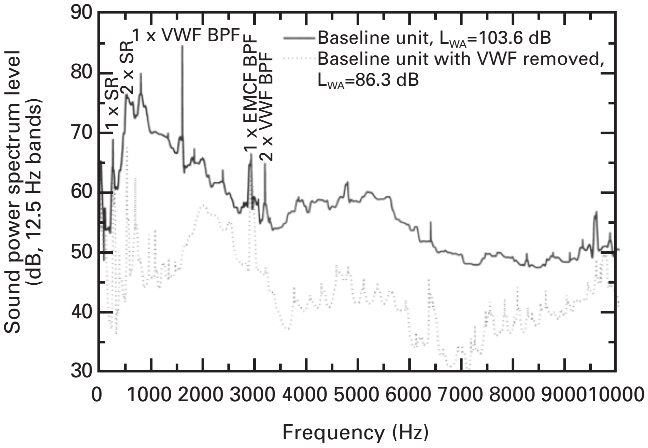


Fig. 3 – Comparison of the sound power radiated by the baseline handheld vacuum cleaner operating under free-delivery flow conditions to the sound power radiated by the same handheld vacuum cleaner operating without its VWF.

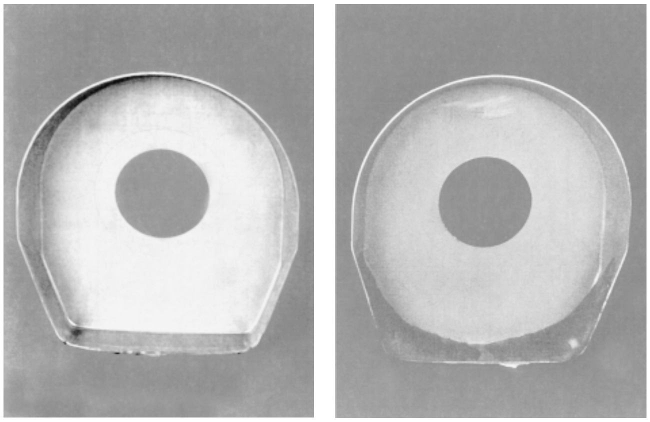
generated tones are contributing at harmonics of the shaft rate but are essentially masked by the aerodynamic noise present when the VWF is operating. The single exception is the tone at the BPF of the electric motor cooling fan (1xEMCF BPF) at 2900 Hz. Figure 2 also indicates that the tone present at the 12th harmonic of the shaft rate with the VWF operating is not motor-generated but is the 2nd harmonic of the VWF BPF (2xVWF BPF).

4. NOISE CONTROL MODIFICATIONS PERFORMED

The noise control modifications performed on the handheld vacuum cleaner focused on reducing the annoyance due to the 1xVWF BPF tone. This tone is particularly bothersome because of its singular dominance and large amplitude. Two approaches were taken to reduce its annoyance: the first approach consisted of reducing the tone amplitude, which was accomplished by performing modifications to the VWF shroud (stone shield) and to the VWF itself. The second approach consisted of introducing additional tones to the sound by spreading the acoustical energy into a number of additional shaft rate harmonics. Typically, wide-band noise with uniform frequency content (white noise or pink noise) is more readily tolerated by humans than noise with distinct tonal components.[6] However, if tonal components are present, it has been concluded that multiple tonal components may be perceived as less loud and annoying than single tones due to the increased masking provided by interactive tones.[7] It has also been shown that not only do multiple tones mask one another effectively, but they are capable of masking broadband noise as well.[7] Thus, people tend to perceive the sound with multiple tonal components as much less annoying than noise with a single, high amplitude, discrete frequency component such as that radiated by fans with evenly spaced blades. Multiple tones at harmonics of the shaft rate frequency may be generated by unequal spacing of the VWF blades.

5. REDUCTION OF THE TONE MAGNITUDE AT THE FAN BPF

It was suspected that the tone at the BPF 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 Fig. 4 along with a photograph of a baseline stone shield for comparison. Figure 5 compares the sound power radiated by the baseline unit to the sound power radiated by the same unit with a stone shield modified as shown in Fig. 4. Figure 5 shows a tone level reduction of 7 dB at the 1xVWF BPF. Tests performed with a number of different units indicated that the sound power level reduction at the 1xVWF BPF ranges consistently from 4 to 8 dB with this particular modification. The stone shield modification resulted in a 2 dB reduction in L_{WA}.



Baseline Modified

Fig. 4 – Comparison of the modified stone shield to the baseline.

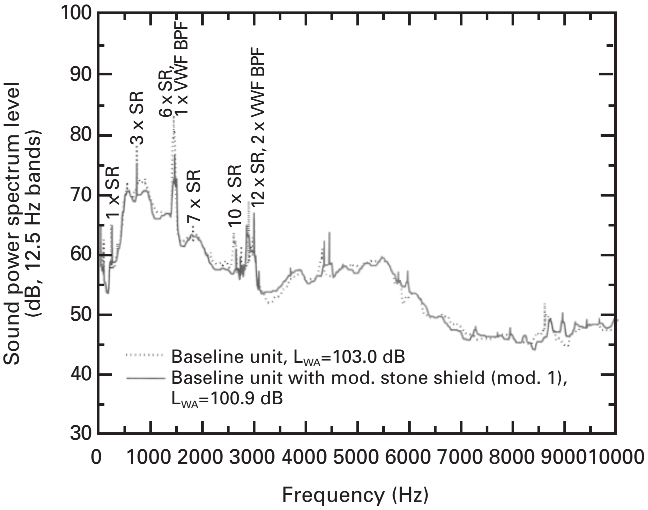


Fig. 5 – Comparison of the sound power radiated by the handheld vacuum cleaner with the modified stone shield to that radiated by the baseline at free-delivery flow conditions.

An alternative means of reducing the magnitude of the 1xVWF BPF tone is to change the number of blades. The success of reshaping the stone shield corners at reducing the 1xVWF BPF tone levels indicates that the 1xVWF BPF tone is produced by an interaction between the six (6) blades of the VWF and the bottom two (2) corners of the stone shield. The VWF's 60° blade spacing and the (mean) 66° corner-to-corner spacing, measured from the fan axis of rotation, results in two blades from the fan being at closest approach to the two corners almost simultaneously. The in-phase interaction between the blades and corners of the stone shield causes the high radiated noise levels. Therefore, a VWF with nine (9) evenly spaced blades was constructed to reduce this problematic in-phase interaction. The 9 bladed VWF was machined from a solid block of acetal plastic with blades geometrically identical to those of the baseline. Figure 6 compares the sound power radiated by the baseline handheld vacuum cleaner to that radiated by the same unit with a 9 bladed VWF. The data show that the 1xVWF BPF tone is reduced 8 dB by the modified fan. In addition to the 1xVWF BPF tone level reduction, and the frequency shift in blade

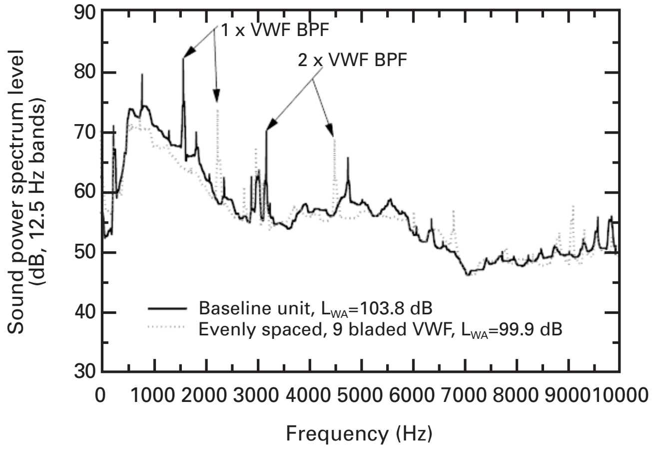


Fig. 6 – Comparison of the sound power radiated by the handheld vacuum cleaner modified with the 9 bladed VWF (even spacing) to that radiated by the baseline.

rate harmonics due to the increased blade number, L_{WA} is reduced 4 dB with this modification.

6. INTRODUCTION OF MULTIPLE TONES TO THE RADIATED SOUND

The tone level reduction achieved with the 9 bladed VWF is approximately the same as that achieved with the 6 bladed VWF operating within the modified stone shield. Because these noise control modifications have not eliminated the VWF BPF tones completely, an attempt was made to mask them. A novel 6 bladed vacuum working fan with unevenly spaced blades was 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.[8] The blade locations vary up to ± 9º from its evenly spaced counterpart. Both fans are shown in Fig. 7.

Deviation angles occur at the rotor exit because the air is not discharged at the blade angle, but rather at an angle which depends on the blade camber and solidity. All other parameters being equal, an increase in blade number decreases the blade deviation angle while increasing the fan input power requirements. The reduced deviation angle implies a larger pressure rise. Alternatively, in the mean, uneven blade spacing of the same blade number will not alter the fan aerodynamic characteristics or vacuum cleaner performance.

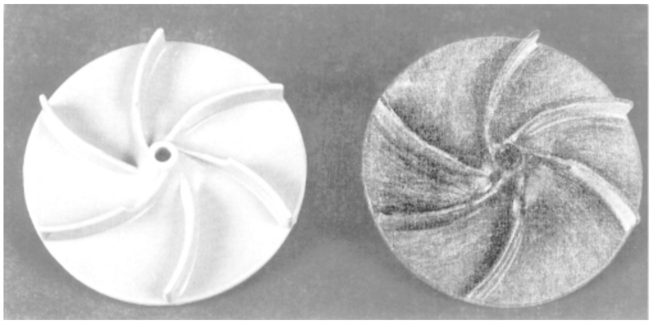


Fig. 7 – Comparison of the unevenly spaced 6 bladed VWF to its evenly spaced counterpart.

Figure 8 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 shown in Fig. 4. As expected, these modifications generate numerous tones at harmonics of the shaft rate frequency and L_{WA} is reduced 2 dB. Because the Fig. 8 results do not provide a direct measure of how people perceive the sound from the modified unit, additional subjective means of quantifying the radiated sound are needed.

7. JURY EVALUATION

The perceived loudness of individual tones may be quantified from pure tone equal loudness curves.[9] These curves account for, among other issues, the reduced sensitivity of human hearing at low frequencies, and the increased sensitivity of the ear near the fundamental resonance frequency of the ear canal at 4 kHz. While the equal loudness curves can quantify how loud individual tones will sound to the average human with good hearing, they cannot be used to quantify the human response in terms of the acceptability of a sound, or the preference of one sound over another. This is true, in particular, for sound containing both broadband noise and multiple pure tones, such as that radiated by the handheld vacuum cleaners considered here.

A number of objective calculation procedures exist for assessing the level of acceptability or annoyance of a sound, one of the most widely accepted being the Stevens Mark VII.[10] Hellman[7] points out that all objective procedures known at the time of her writing, including the Stevens Mk VII, were, at best, only marginally successful at predicting subjective responses as evidenced by her results. Investigators feel that in some cases the disagreement between the objective and subjective measures of annoyance are due to the inappropriate weighting of the line components in the spectra considered. The psycho-acoustic metrics such as loudness, sharpness, fluctuation strength, and roughness are used to define the psychoacoustic annoyance of a sound.[11] While such a

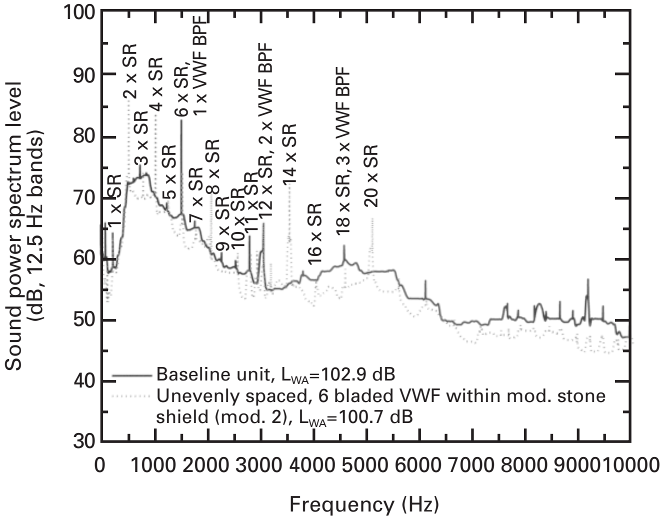


Fig. 8 – Comparison of the sound power radiated by Mod. 2 to that radiated by the baseline.

combination of metrics may prove more effective at predicting annoyance than any single metric, Lyon points out that sound quality is product specific and the metrics used to interpret the sound quality may not be the scale the customer is using.[12] Therefore, the most effective means of quantifying product annoyance and the preference of one product 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 Fig. 4. Modified unit No. 2 (Mod. 2) consisted of the unevenly spaced 6 bladed VWF shown in Fig. 7 operating within the modified shield shown in Fig. 4. The sound power radiated from Mods 1 and 2 are shown in Figs. 5 and 8, respectively. The average loudness levels of the most prominent tones, calculated from the charts of Beranek,[9] are presented in Figs. 9 and 10. An overall average tonal loudness level (OATLL) is computed from these figures by simply adding together the energy indicated in each presented frequency band. The OATLL is reduced 1.5 dB from the baseline level with Mod. 1, however, Mod. 2 *increases* the OATLL 6 dB from the baseline level. The Mod 2 modifications result in a monotonically decreasing harmonic series of tone levels to the 4th order with the fundamental tone at the 2nd harmonic of the shaft rate. With the exception of the motor-generated line component at 11 x SR, tones at the 12th, 14th and 20th harmonics of SR are the only other significant tones present.

A. Jury evaluation method

Thirty-three men and seven women were selected at random from the faculty, staff, and students at Penn State University to form an informal jury. The subjects ranged in age from approximately 19 to 62 years and not all had acute hearing. Those individuals with a substantial knowledge of this particular phase of the project were excluded. 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, lift it off the table, hold it at waist-to-chest height, turn it on and listen to it, and then turn it off and return it to the table. The subjects were then instructed to 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. Most subjects did this several times for each unit.

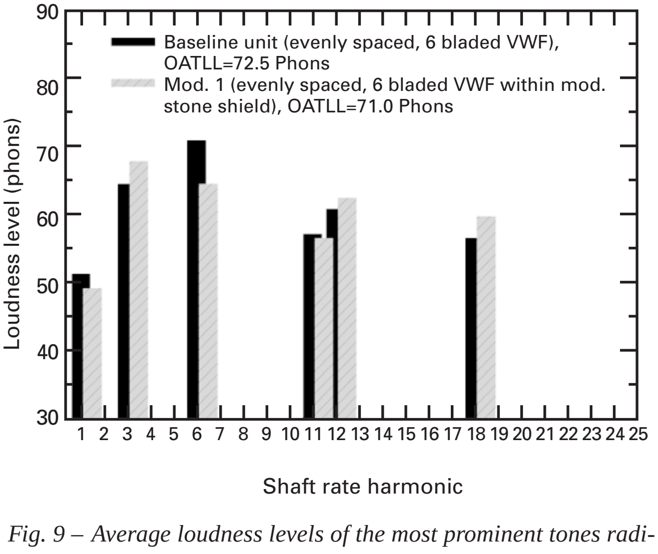


Fig. 9 – Average loudness levels of the most prominent tones radiated by Mod. 1 to that radiated by the baseline.

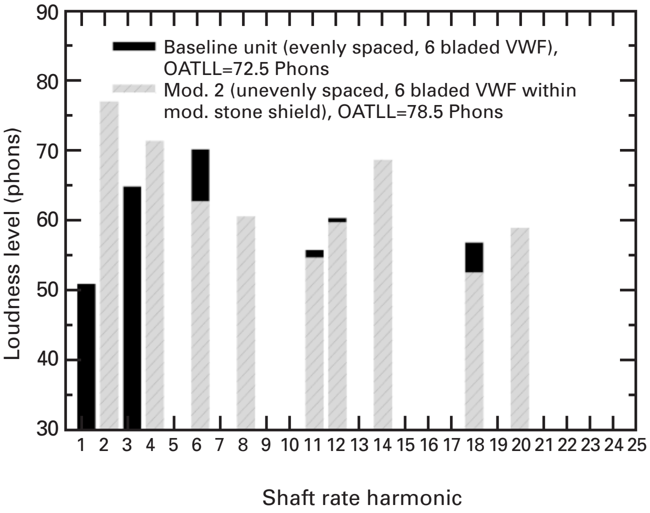


Fig. 10 – Average loudness levels of the most prominent tones radiated by Mod. 2 to that radiated by the baseline.

B. Jury evaluation results

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 its L_{WA} is equal to that of Mod. 1 and its OATLL is 6 dB greater than that of the baseline unit, and 7.5 dB greater than that of Mod. 1. Over half (52.5%) of those questioned thought the sound from Mod. 2 was the least annoying, while 30.0% preferred the sound from Mod. 1, and 17.5% preferred the baseline unit. The percentages were identical when the subject was asked which unit he/she would purchase based upon the sound. If a subject indicated that his/her purchase would not be influenced by the sound emitted, as 25% did, a forced choice was initiated. The subjects' impression of the power of the three units was less varied. Forty percent of the subjects thought that Mod. 1 sounds most powerful followed by 32.5% and 27.5% for Mod. 2 and the baseline unit, respectively.

The above jury survey results are supported by the results from an earlier, interim jury survey in which the baseline unit, Mod. 2, and the baseline unit modified with an unevenly spaced 9 bladed VWF were tested. The unevenly spaced 9 bladed VWF was not included in the final jury survey due to its accidental destruction during testing. The results from the interim survey also indicated a strong dislike for the baseline unit's radiated sound, where 79% of the subjects indicated they would prefer to purchase one of the other two units.

TABLE 1 – Questions asked in the jury survey.

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 2 – Results from the jury survey.

	Baseline	Mod. 1	Mod. 2
L_{WA} (dB re 1 x 10^{-12}W in 12.5 Hz Bands)	103.6	100.9	100.7
OATLL (Phons)	72.5	71.0	78.5
Rating	%/# votes	%/# votes	%/# 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)

75.0% (30/40) indicated that the sound would influence their decision of which unit to purchase

8. 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 BPF of the VWF was identified as the most annoying component of the radiated sound.

Noise control modifications focused on either reducing the strength of the 1xVWF BPF tone and/or introducing additional tones designed to mask the BPF tone. Appropriately filling-in and reshaping of the corners of the stone shield reduced the 1xVWF BPF tone level by up to 8 dB. Reducing the in-phase interaction between the VWF blades and the stone shield corners through use of a 9 bladed VWF reduced the 1xVWF BPF tonel level 8 dB as well. 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 OATLL of this unit is actually higher than that of the annoying baseline unit by 6 dB.

The results show rather clearly the value of jury testing for assessing the quality of sound from a product and the importance of the tones in that assessment. Values of L_{WA} and OATLL were not effective metrics in quantifying the preference of one vacuum cleaner sound over the other. Utilizing complex tones to mask and reduce the annoyance of singularly dominant tones warrants further investigation.

9. ACKNOWLEDGMENT

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