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ACTIVE CONTROL OF NOISE FROM A VACUUM CLEANER

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Abstract

Vacuum cleaners are noisy and disruptive appliances. Safety regulations, personal comfort and consumer demand are motivation to lower sound emissions from such products. The noise generated from a typical vacuum cleaner mainly consists of broadband random noise and tonal noise. Traditional passive control methods involving absorptive materials are unsuitable for reducing low frequency noise from vacuum cleaners since the bulk of such materials would disrupt airflow thus deteriorating performance. Conversely, active noise control (ANC) can be installed without decreasing airflow rate. Active noise control has been implemented in an industrial backpack vacuum cleaner. The aim is to attenuate a low frequency tonal component to reduce the annoyance while reducing the overall noise level. Experiments conducted in the feasibility study show that the tonal component can be reduced by about 15 dB to broadband level at the error microphone. Importantly, global attenuation can be achieved when the control system is confined to a duct around the lower body of the vacuum cleaner. However, the overall noise level is only reduced by about 2 dB(A). Sound intensity measurements show that although random flow noise is a major contributor, structural vibration of the upper body and lid outside the duct also contributes to structure-borne noise radiation at the tone. To reduce the overall sound level, the noise control strategy must therefore include passive control methods such as absorptive materials and structural redesign to address structure-borne and flow noise.

INTRODUCTION

Vacuum cleaners are a source of annoyance and unwanted noise. A reduction of this noise has many advantages especially in commercial applications. Manufacturers can gain a competitive edge, increasingly stringent health and safety regulations can be met and cleaning can be carried out during normal business hours thus reducing cleaning costs.

Vacuum cleaner noise consists of three main components: airborne, from air movement caused by the centrifugal fan and motor rotation; structure borne, from the vibration of the housing excited by the unbalanced rotation of the motor and fan; and mechanical, such as commutator brush friction and bearing noise [2], [7], [8]. The overall result is a sound spectrum containing random broadband noise with higher level tonal components.

The noise from vacuum cleaners can be reduced through improvement in the design. The overall noise level from a handheld vacuum cleaner was reduced by changing the interaction between the blades and the fan volute thus lowering the magnitude of the blade passing frequency (BPF) tone [2]. Another method was to mask the tone by introducing additional tones. This distributes acoustical energy into a number of tones and decreases perceived loudness. The overall sound power level was reduced by 2 dB(A) to 4 dB(A) by each of the modifications.

Sarbu & Kraft (1996) focussed on both the source and sound transmission paths in a drum type vacuum cleaner to remove pure tones from the sound spectrum and reduce overall noise [8]. Structure borne noise was reduced by upgrading the motor balancing. They used an experimental comparison of the noise to choose the blade profile, outlet casing and other component shapes. The interior of the vacuum cleaner was lined with felt and porous material to reduce reverberation and noise transmission through the frame. A reduction in sound power level of 5.7 dB(A) was measured.

If further noise reduction is required in particular at the tonal peaks, traditional passive control methods involving absorptive materials may become unsuitable. Their use would disrupt airflow and thus deteriorate functionality. Conversely, active noise control can be installed without decreasing airflow rate. Joo *et al.* (1994) demonstrated implementation of broadband feedforward active control in a vacuum cleaner by setting up a duct system inside the vacuum cleaner body [5]. The FXLMS algorithm updated filter coefficients and the researchers encountered problems with the spatial constraints and reference signal quality. Vibration isolation was redesigned to reduce structural noise and improve the active noise control system performance. The system achieved some positive results and demonstrated potential for ANC in a domestic type vacuum cleaner. In the present work ANC is applied to a backpack vacuum cleaner to reduce the annoyance from the low frequency tonal component.

NOISE CHARACTERISTICS

The objective of this study is to investigate the feasibility of using an active noise control (ANC) system in a Pac Vac vacuum cleaner. A photograph of the vacuum cleaner is shown in Figure 1. It is designed for industrial use and is worn as a backpack. This model consists of a small and fast motor housed in the lower cavity. Suction is created by rotation of a 9-blade centrifugal fan powered by the mains supplied motor. Air containing dirt enters the vacuum cleaner body through a hose, moves through three increasingly fine air filters before interacting with the fan and motor and is expelled through air vents. The motor has a maximum rotation speed of 47000 rpm and its rotation speed depends mainly on the load on the vacuum cleaner.

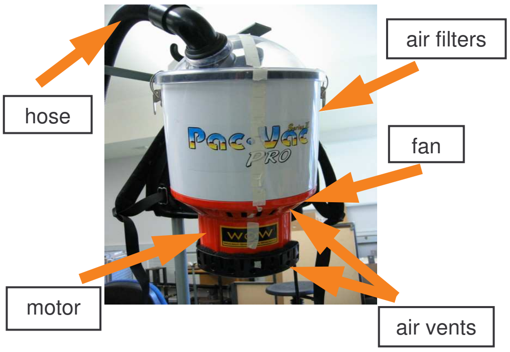


Figure 1 – Photo of vacuum cleaner

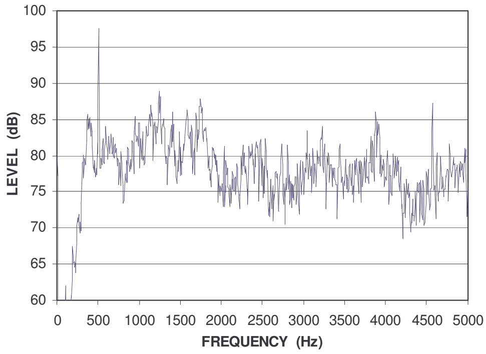


Figure 2 – A-weighted spectrum at 1 m

Noise Spectrum

A typical A-weighted noise spectrum of the device measured in an anechoic chamber is depicted in Figure 2. The result shows the presence of 2 tonal peaks around 510 Hz and 4600 Hz. The first tonal component dominates the noise spectrum by over 10 dB. This can be a main cause of annoyance to cleaners or occupants of a room and cannot be reduced significantly by applying passive absorption alone without an increase in the size of absorbent and flow resistance and therefore back-pressure. On the other hand ANC can be used to reduce this frequency effectively without adding bulky absorption material. The second peak (4600 Hz) can be treated more effectively by addition of some passive absorption to reduce its level thus lowering its net contribution to the overall noise level.

Global directivity

In view of using ANC to reduce the 500 Hz tone, the global directivity was obtained from the sound pressure level measured over 62 points, at 1m radius from the source operating in the anechoic chamber [3]. These points circled the source in 30 degrees intervals in both horizontal and vertical directions. Figure 3 shows the magnitude of the A-weighted sound pressure level at the tonal frequency at each measured point.

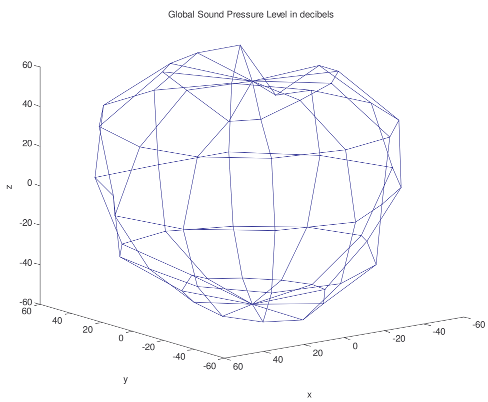


Figure 3 – Magnitude of A-weighted sound pressure level of first tonal peak in dB

The measurements show that the distribution is of similar shape to that of a monopole. Although the unevenness does not outline any nodes, lobes or highly directional locations these measurements illustrate that the sound is not from an ideal point source. This can be expected since the vacuum cleaner is a complicated appliance. The top half of the shape in Figure 3 is wider when compared to the ideal monopole and can be related to the vibration of the large structural surface area above the fan and motor. There is also an indent in the shape where there is less noise radiation due to the hose connection point. Results from this experiment shape the acoustic activity of the vacuum cleaner and suggest that a single loudspeaker may be sufficient to control the 510 Hz tone.

ACTIVE NOISE CONTROL SYSTEM

The directivity experiment revealed that the source can be approximated to a monopole at 510 Hz. A simple ANC system was set up to investigate the performance under such an assumption. In particular, it is useful to know if control is possible, if control is global and how effective the control is.

Experimental Setup

The aim of the ANC experiment was to reduce the tonal magnitude around 510 Hz. A feedforward adaptive controller with 1 reference sensor, 1 error microphone and 1 loudspeaker, including online system identification, was employed during testing in an anechoic chamber [6]. Structural vibration picked up from an accelerometer located on the body of the vacuum cleaner was used as a reference signal. An error microphone was located 1 m away from the vacuum cleaner such that the coherence between its signal and the reference signal was greater than 0.9 at 510 Hz. A digital signal processor (DSP) was used to implement the adaptive control algorithm. Other equipment included pre-amplifiers, a power amplifier and low-pass filters. A schematic of the experimental setup is given Figure 4.

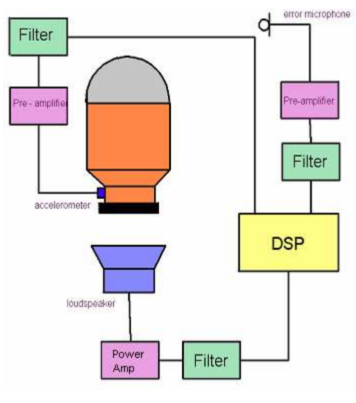


Figure 4 – Schematic of ANC system

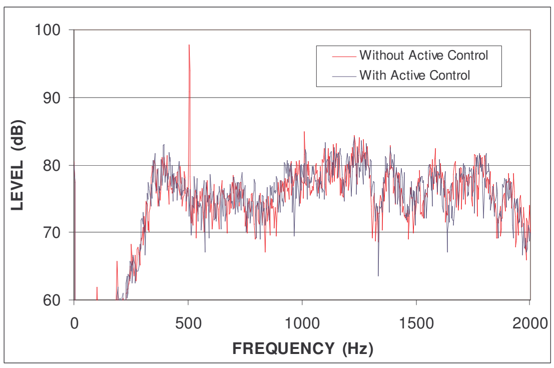


Figure 5 – A-weighted spectrum with and without ANC measured at the error microphone

Results

The active control system was successful in reducing the tonal noise at 510 Hz at the error microphone as shown in Figure 5. The tonal peak has been reduced by more than 15 dB down to broadband levels. The effect of the control was clearly audible at the error microphone as the annoying 'whine' was eliminated. To investigate the global nature of the ANC, sound pressure level measurements were made at eight equally spaced locations around the vacuum cleaner at 1 m radius, as well as at the error microphone and at two random points. The experiments were repeated with (1) the error microphone moved further and, (2) the loudspeaker moved closer to the vacuum cleaner. The results showed that at almost all measurement locations, except 5, there were increases in the noise level at 510 Hz. Hence it is clear that the ANC did not produce global control [3].

Global Active Noise Control

In an attempt to achieve global control a duct was fitted to the bottom of the vacuum cleaner to allow plane wave propagation. Active noise control was implemented in the duct with the aim of reducing the tonal frequency component globally. A schematic of the active noise control setup is shown in Figure 6.

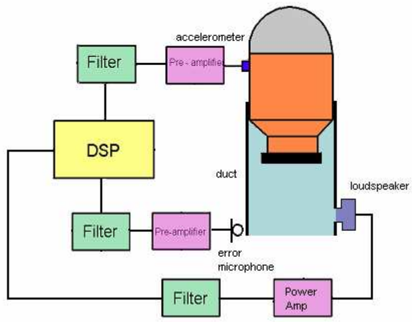


Figure 6 – Schematic of ANC setup with duct

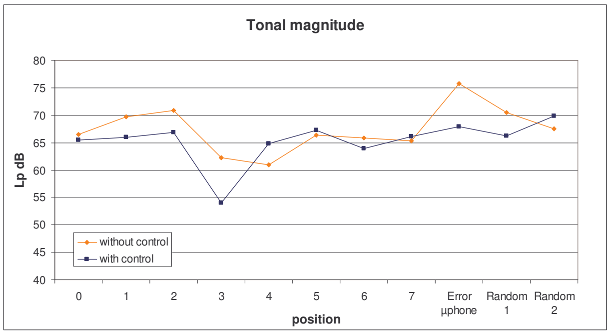


Figure 7 – A-weighted tonal magnitude at each measurement point

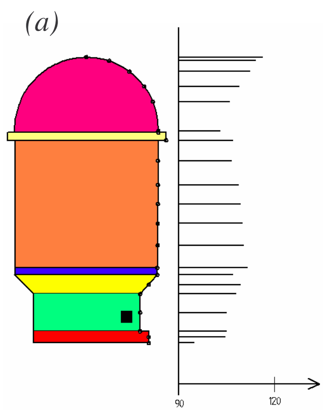
The error microphone was located at the duct exit away from the airflow and a loudspeaker attached to the side of the duct. Using an accelerometer as reference sensor, ANC results show that the tonal peak around 510 Hz was attenuated by about 10 dB to broadband levels similar to the plot previously obtained in Figure 5. The difference between the tone and the broadband noise however is less significant than without the duct because the error microphone was placed near the duct, where airborne broadband noise is the main component of the propagating sound.

Sound pressure level measurements were made at eleven locations. Figure 7 compares the magnitude of the tone at each point, with and without control. At six of these some attenuation was achieved at the tonal frequency. At two positions, the magnitude was virtually unchanged and at two positions there was a small increase in magnitude. These increases are due to the microphone located at positions of low sound pressure levels before control and due to the background pseudorandom noise used in the online system identification running while control is on.

Apart from eliminating the annoyance of the tonal frequency around 510 Hz, it is also desirable to reduce the total sound level. At seven of the eleven measurement points, the total level decreases with control. At the remaining locations the total sound level either remains the same or increases slightly with control. A maximum noise reduction of 2 dB(A) was measured with control. The results show that although ANC in the duct gives better global noise reduction than in the original ANC system, the total global noise reduction remained small.

NOISE ANALYSIS

Sound intensity was used to find the sound power radiated by different surfaces of the vacuum cleaner without the duct [1], [8]. The power spectrum for each defined part was analysed in order to rank them in terms of their radiated sound power. The magnitude of the sound intensity was obtained at twenty discrete points along one side of the vacuum cleaner in a vertical plane as shown in Figure 8(a) to obtain an idea of the sound radiated along the vacuum cleaner. The A-weighted intensity was calculated with a 10-second averaging time in one-twelfth octave bands.



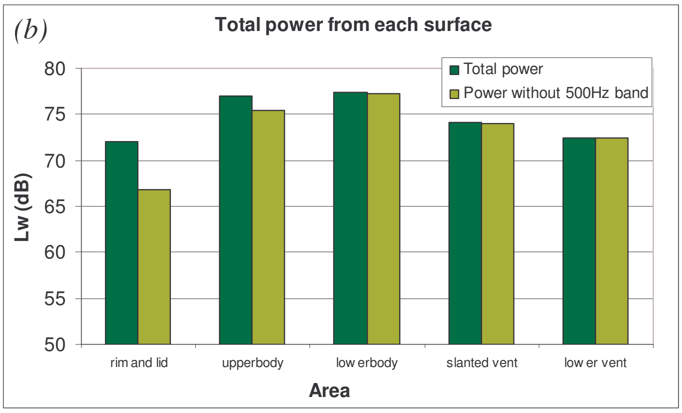


Figure 8 – (a) A-weighted intensity of 500Hz band in dB, (b) total power with and without the 500 Hz tonal band

Results

A plot of the relative magnitude of the measured sound intensity normal to the surface at each point for the 500 Hz frequency band containing the tonal component is shown in Figure 8(a). This result indicates that there is an increase in intensity at the lid, suggesting that there is significant vibration at 510 Hz to produce sound radiation. Also, the intensity is greater at the bottom of the upper body. This is caused by vibration from the upper body as well as airborne noise from the fan.

Six surfaces were chosen on the vacuum cleaner for sound power calculations [9]. These are shown in Figure 8(a) as: the lid in pink, the rim in pale yellow, the upper body in orange, the slanted vent in bright yellow, the lower body in green and the lower vent in red. For each defined surface, a single time averaged intensity value was measured using spatial averaging. This was achieved by steadily sweeping a B&K 3520 intensity probe across the surface [1] and a B&K 2144 frequency analyzer. The spatially averaged intensity was repeated three times for each of the six sections in A-weighted 1/3 octave bands up to a 10 kHz centre frequency band. The sound power was then calculated for each surface area at each frequency band.

Figure 8(b) shows the total power for each surface next to the corresponding total power without the 500 Hz bandwidth and reveals the extent that the tonal frequency contributes to the power radiated at that surface. The lower body is the greatest radiator of sound power, followed closely by the upper body. Next are the slanted vent, lid and lower vent. The sound power from the rim and lid has been combined into a single component (lid). Figure 8(b) shows that for the lid and upper body the 500 Hz band, contributes by about 5 dB and 2 dB respectively to the total sound power. However, for the lower body and the vents, the tonal noise is a small part of the total noise from these surfaces. This supports the results from the active noise control implementation where removal of the tone did not decrease the total sound pressure level satisfactorily at all measurement locations. That is, although global noise reduction was achieved at the tonal frequency thus reducing annoyance, the effect on the total sound pressure level was minimal.

The noise analysis carried out with intensity measurements to obtain the radiated sound power from specific surfaces shows that:

- the lower body radiates the largest amount of sound power. However, the tonal component around 510 Hz is not a significant contributor.
- the 510 Hz tonal component dominates the sound spectrum for the lid and upper body surfaces. This can mainly be attributed to the structural vibration of the lid and upper body causing the structure borne noise at that frequency.
- removing the 510 Hz frequency from the sound spectrum would reduce the total radiated power from the lid and upper body, but not from other surfaces.
- the high level of broadband noise caused by airflow dominates the total sound level. As a result when the 510 Hz component is removed, the overall noise level is not significantly affected.

SUMMARY

In this paper ANC was applied to control the noise from a backpack vacuum cleaner. In particular the aim was to attenuate the tonal frequency component around 510 Hz in order to reduce annoyance. Localised control of over 20 dB reduction was achieved at that frequency with the secondary source mounted outside the vacuum cleaner. Although at the error microphone the control was clearly audible at many other locations away from the vacuum cleaner the noise either did not reduce or even increased. To achieve global control a duct was fitted to the lower body. The ANC was able to reduce the tonal component at the error microphone by about 10 dB and better global noise reduction at this frequency was obtained at other locations. However, the overall noise level was only reduced by up to 2 dB(A).

A noise analysis identified the main sources of noise radiation from the Pac Vac vacuum cleaner. Sound power measurements have shown that the lower body is a significant source of noise. However, the 510 Hz airborne component does not dominate its radiated sound but broadband flow noise from the lower body and vents does. On the other hand, the upper body and lid are main sources at that frequency. Since the control aim was to attenuate the tone in the duct, it did not include the structure borne tonal component from the lid and body. This was still present at locations outside the duct. Although it is possible and desirable to remove the tonal component which is a source of annoyance, it is also necessary to reduce the broadband noise in order to decrease the total noise level.

Current ongoing work includes passive control methods: firstly to reduce the structural vibration and secondly to reduce the broadband noise, especially at higher frequencies. It is anticipated that once broadband noise is lowered, the annoying tonal frequency component will dominate the overall sound level. A combination of passive treatment and structural redesign with active noise control can then be applied to achieve improved global noise reduction from the vacuum cleaner.

ACKNOWLEDGEMENTS

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