A compact active control system for tonal noise reduction in axial fans

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The objective of this paper is to show the feasibility of active control of tonal noise from automotive engine cooling fans using a single unbaffled loudspeaker in front of the fan. A simplified model is described for preliminary design using this configuration. A single input single output (SISO) filtered X-LMS has been implemented to control the first tones in real time. At the error microphone, the sound pressure attenuation at blade passage frequency (BPF) and its first harmonics are reduced down to the broadband noise level. At low frequency, for large sound wavelength compared to the fan radius, the sound radiation is reduced in all directions, since the dipolar directivity of the secondary noise emitted by the unbaffled loudspeaker is similar to the directivity of the primary noise emitted by the fan.

INTRODUCTION

The first studies on active control of noise generated by ducted axial fans have been conducted in the 80's [1]. As long as a plane wave can be considered to propagate in the duct, i.e. below the cut-off frequency of the duct, a single loudspeaker can be used as the secondary source. When higher order modes propagate in the duct, more loudspeakers are required to control all the propagating modes. Recently, studies have been carried out to actively control the tonal noise radiated by the exhaust fans [2], computer fans [3,4], or engine cooling fans [5,6]. The directivity of the fan noise radiation must be taken into account to efficiently control the sound in the whole space. In ref. [3], a MIMO system was implemented to globally control the first four tones of a cabinet fan, using four loudspeakers and multiple error microphones. In this paper, the use of a single unbaffled loudspeaker is considered to globally control the first two tones of an engine cooling fan in free field. The primary tonal noise emitted by the fan is first described. Then, simulation results are presented from a simplified model of the fan noise and the secondary source. Finally, the experimental active control arrangement is described, and active control results in free field are presented.

1. TONAL NOISE FROM SUBSONIC AXIAL FANS

It is important to first characterize the directivity of the noise to be controlled to adequately determine the number and locations of secondary sources and error sensors for the implementation of the active control strategy.

For subsonic fans, tonal noise at BPF and its harmonics mainly originates from the non-uniform stationary part of the flow entering the rotor which causes periodic changes in blades' angle of attack, thus producing cyclic blade loading variations. Non uniform flows are usually encountered in practice when the rotor operates upstream or downstream struts, radiator, engines… The loading variations can be analyzed in terms of circumferential loading modes, as described in [7]. From the Ffowcs Williams and Hawkings analogy, the loading fluctuations generate dipolar sources of sound on the blades.

As long as the chord of the blades (C) is small compared to the acoustic wavelength, the rotor can be approximated by rotating dipole lines along the span. Moreover, if the blade span L is also small compared to the sound wavelength λ, the fan can be considered compact compared to the span. Thus the rotor can be approximated by rotating dipole points.

In the case of acoustically compact fans, two types of noise generation mechanisms can be pointed out, depending on the circumferential periodicity of the flow entering the fan, thus depending on circumferential loading modes. First, when all the blades experience **in-phase loading variations**, constructive interferences are produced; this is the case for the circumferential loading mode having the same number of maxima as the number of blades. In this case, all the elementary dipoles are in phase leading to a strong overall axial dipolar directivity. In contrast, when the loading variations change from blade to blade, which is the case for circumferential loading modes having a number of maxima different from the number of blades, destructive interferences occur. The overall radiated tonal noise due to these **phase-shifted loading variations** is smaller and its directivity is not dipolar. In practice, all the circumferential loading modes are summed, which generally lead to an overall dipolar noise shifted from the fan axis at low frequency.

The fan directivity can become more complicated at medium and high frequency since the non dipolar acoustic radiation due to the phase-shifted loading variations increases in magnitude relatively to the dipolar radiation due to the in-phase loading variations. Moreover, the directivity of the overall radiated noise can also be complicated for acoustically non-compact fans by interferences between the sound radiations from various areas of the fan.

2. ACTIVE CONTROL SIMULATIONS USING A SIMPLIFIED FAN NOISE MODEL

The exact acoustic radiation of the fan can be calculated if the relative contributions of the circumferential blade loading modes are known. This is difficult to predict analytically or by computational fluid dynamics calculations. As an alternative, the acoustic directivity of the fan can be measured to perform active control simulations accurately. Inverse modelling also permits to retrieve the relative contribution of the most radiating circumferential loading modes and to extrapolate the radiated noise in the whole space from a finite set of far field sound pressure measurement points, which is useful for accurate active control simulations [5, 8].

However, for a preliminary investigation of active control, the simplified fan noise model described in [6] can be used as a first approximation: Since a large part of the low frequency tonal noise is dipolar for acoustically compact fans, the use of another dipole of equal magnitude but opposite in phase and located close to the center of the fan is appropriate for global active control. A compact control solution consists of locating a dipolar unbaffled loudspeaker at a small axial distance z_s from the fan center (Fig. 1).

In this section, a simplified primary dipolar radiation of the fan (in phase dipoles rotating at a mean radius of $\bar{r}_1$ = 1.25 cm) and a simplified secondary dipolar radiation of the unbaffled loudspeaker (a piston of radius a=4cm) are considered (Fig. 1). This situation is representative of a typical automotive engine cooling axial fan. The resulting acoustic directivity is the superimposition of the fan and loudspeaker acoustic radiations [6] when minimizing the acoustic pressure at error sensor locations (r, θ_l).

Fig. 2 shows the primary, the secondary and the resulting directivity plots for various numbers and locations of the error microphone(s) (circles in Fig. 2) for a BPF of 300 Hz radiated by a 6-bladed automotive engine cooling fan in free field.

Figs. 2.a and 2.b show that the spatial directivity of the control source reasonably matches the directivity of the simplified fan noise model, resulting in a significant sound attenuation in the error microphone located in the downstream half-space. In Figs. 2.a and 2.b, the attenuations are maximal at the error sensor, for angular positions $\theta_0 = 0$ and $\theta_0 = \frac{\pi}{3}$.

Figs. 2.c and 2.d show that the use of distributed downstream and upstream sensors is more efficient to control both the upstream and downstream sound fields. However, if the objective is to control the sound radiation in the downstream half space, the use of multiple error microphones does not improve the control performance.

Fig. 3 shows the primary, secondary and resulting acoustic directivities at 2xBPF=600 Hz. Using a single downstream error microphone is effective in controlling the acoustic radiation in the downstream half space but negligible attenuation is achieved in the upstream half space (Fig. 3.a). Using upstream and downstream error microphones leads to global attenuations in both half spaces (Fig. 3.b).

For higher harmonic orders of the BPF, increase in sound level is expected in the upstream half space when using a single microphone in the downstream half space. More microphones can be used to globally control the tonal noise at these higher frequencies. However, such higher frequencies can be passively attenuated more efficiently and cost effectively than with an active control solution.

The simple model described previously provides a useful tool for a preliminary design and understanding of the active control of tonal fan noise, when a single unbaffled loudspeaker is located in front of the fan.

3. ACTIVE CONTROL EXPERIMENTS IN FREE FIELD

3.1. EXPERIMENTAL SET-UP

Experiments were conducted on a symmetric 6-bladed automotive fan or a non-symmetric 7-bladed automotive fan, with a radiator located in front of the fan. In the experiments with the 6-bladed fan, a small (4x8 cm) rectangular piece of adhesive tape was bonded on the upstream side of the radiator at about 5 cm from the fan axis in order to enhance the non-uniformity of the incoming flow and therefore increase tonal noise radiation. The fan unit was driven by a variable DC source (0-20V/0-60A); the rotational speed of the

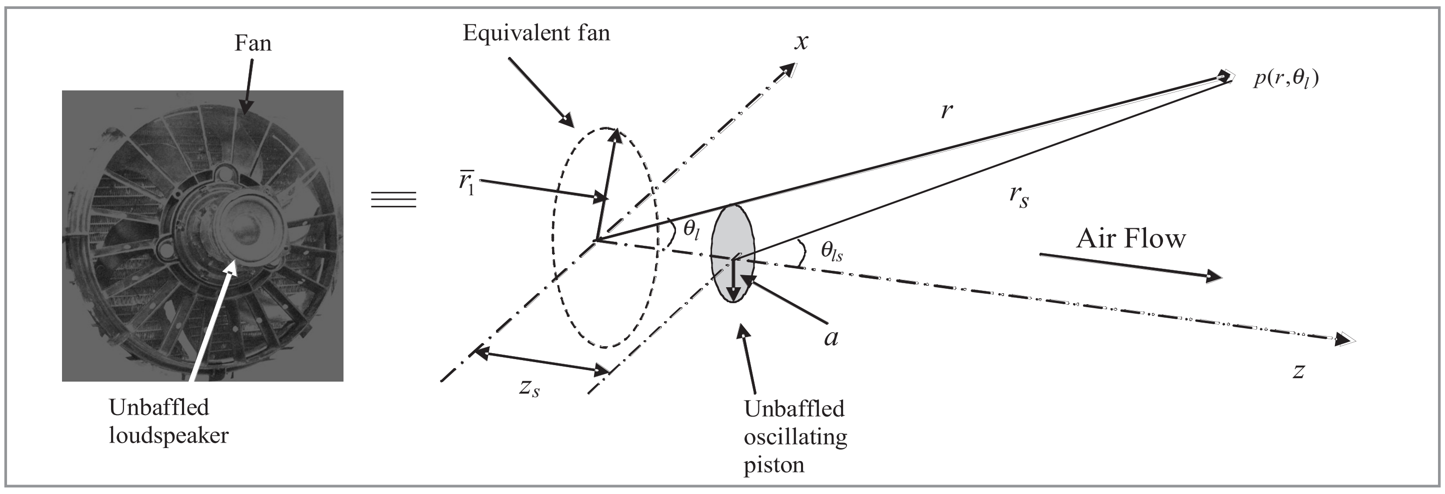


Figure 1. *Active control arrangement for free field fan noise control.*

fan could be continuously adjusted by modifying the input voltage. The fan has an exterior diameter of 30cm and a central hub diameter of 12.5cm.

A small midrange unbaffled control loudspeaker of 8cm in diameter was bonded to the fan hub. The average distance between the plane of the blades and the loudspeaker membrane was z_s = 5cm. It was verified that the loudspeaker has a negligible effect on the downstream flow of the fan; in the reported results, all noise data of the fan alone were measured with the control loudspeaker in place. A SISO adaptive feedforward controller was implemented to drive the control loudspeaker. An infrared optical tachometer was mounted on the fan in order to extract a reference signal containing the relevant frequencies. In the case of the 6-bladed symmetric fan, 6 pieces of reflective tape were equally distributed on the outer rim of the fan, so that the reference signal is a train of rectangular pulses with a fundamental frequency equal to the blade passing frequency. In the case of the 7-bladed fan with unequal blade pitches, the reference signal must be designed to contain multiples of the rotational speed of the fan, with important components at multiples of the BPF: this was achieved by unequally distributing 7 reflective strips on the outer rim.

An error microphone (TMS

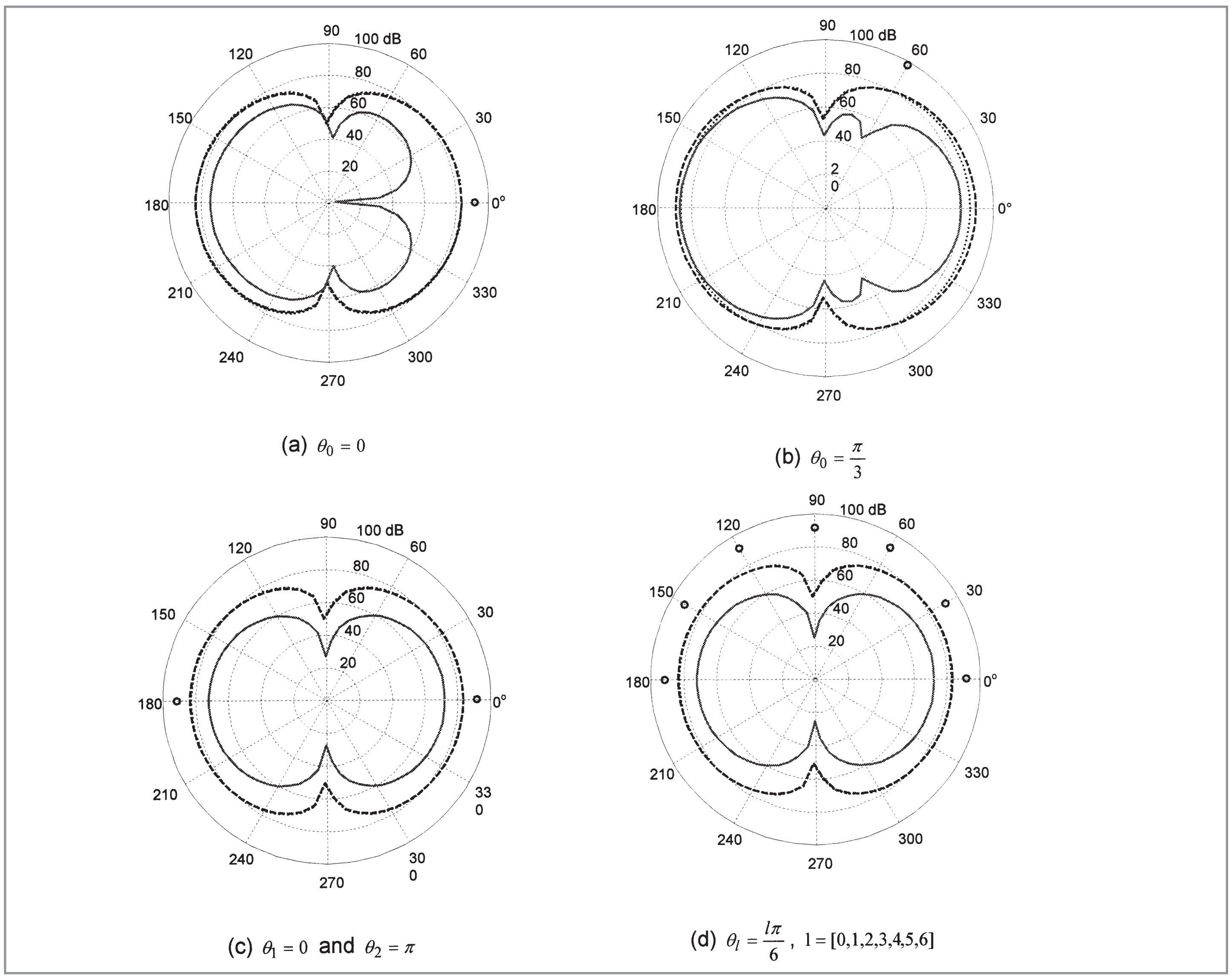
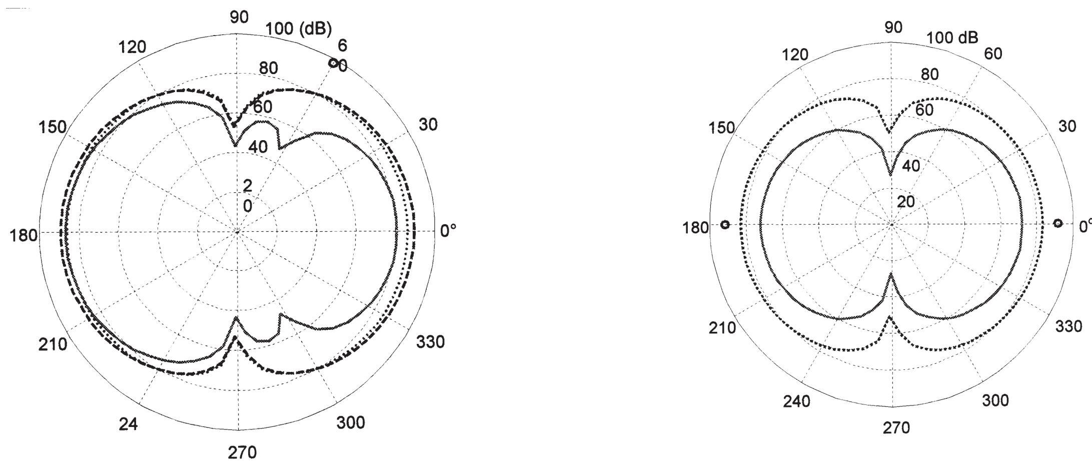


Figure 2. Far field sound directivity for various error microphone configurations at f=300 Hz; Primary field (dashed), second field (dotted) and global (solid). $\lambda/z_s = 23$, $\lambda/a = 28$ and $\lambda/\bar{r}_1 = 9.4$.

1/4"made by PCB) was located at 1.5m from the fan centre in the downstream half-space; the microphone could be moved at various directions θ_0 from the fan axis. A windscreen was mounted on the microphone to minimise the effect of flow noise. The physical elements of the feedforward active control set-up are shown in Fig. 4. The set-up was placed in a semi-anechoic room with the fan axis horizontal and at 50 cm above the ground. 12 cm of absorbing material (conasorb F) was laid on the ground under the set-up order to minimise ground reflections.

Active control simulations for this configuration have shown that global control of the downstream sound field can be obtained up to approximately 700Hz using a single control source. Given that the rotational speed was set to approximately 50Hz, the experimental objective was therefore a global attenuation of downstream noise at 1xBPF and 2xBPF. A time-domain adaptive filtered-X LMS feedforward



(a) $\theta_0 = 0$ (b) $\theta_1 = 0$ and $\theta_2 = \pi$

Figure 3. Far field sound directivity for various error microphone configurations at f=600 Hz; Primary field (dashed), secondary field (dotted) and global (solid).). $\lambda/z_s = 11$, $\lambda/a = 14$ and $\lambda/\bar{r}_1 = 4.7$.

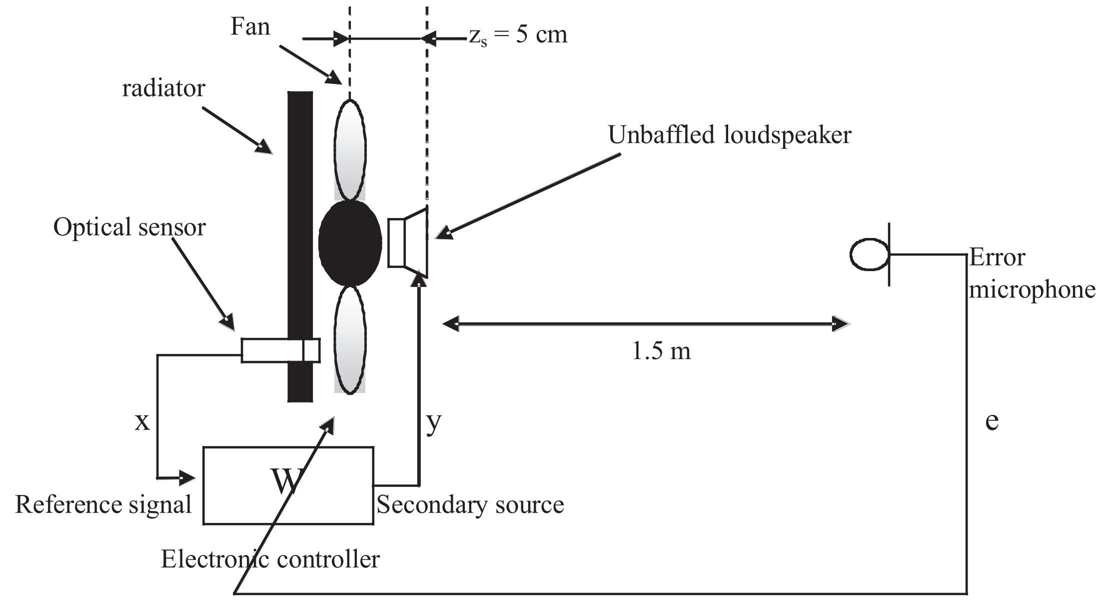


Figure 4. Physical elements of the single channel feedforward active control of free field fan noise.

controller [6] was implemented under a dSPACE/Simulink real-time control environment. The sampling frequency was set to 3000Hz, and anti-aliasing and reconstruction low-pass filters were used at input and output stages of the digital signal processing board. The cut-off frequency of the low-pass filters was set to 800Hz in the case of the 6-bladed fan and 1200Hz in the case of the 7-bladed fan. The secondary path (transfer function between loudspeaker input and error microphone output) was identified off-line by feeding a broadband noise to the secondary source and using an adaptive LMS identification with a 64-tap FIR filter. The control filter was implemented as an FIR filter with 4 coefficients (6-bladed symmetric fan) or 32 coefficients (7-bladed non-symmetric fan). The measured coherence between the reference sensor and the error microphone at 1xBPF and 2xBPF was

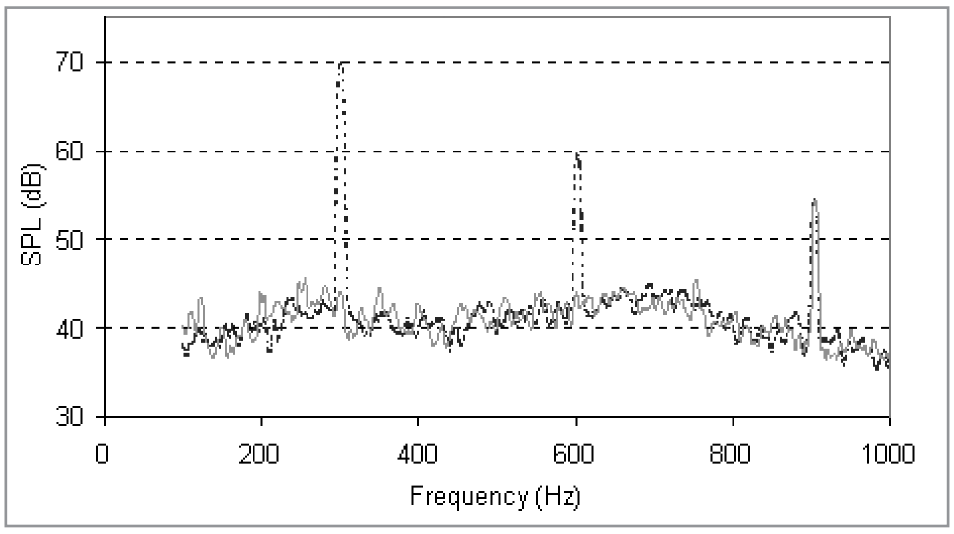


Figure 5. Power spectrum of the sound pressure at the error sensor position (θ_0=0) for a 6-bladed (with equal pitches) automotive fan noise, with (solid line) and without (dashed line) active control.

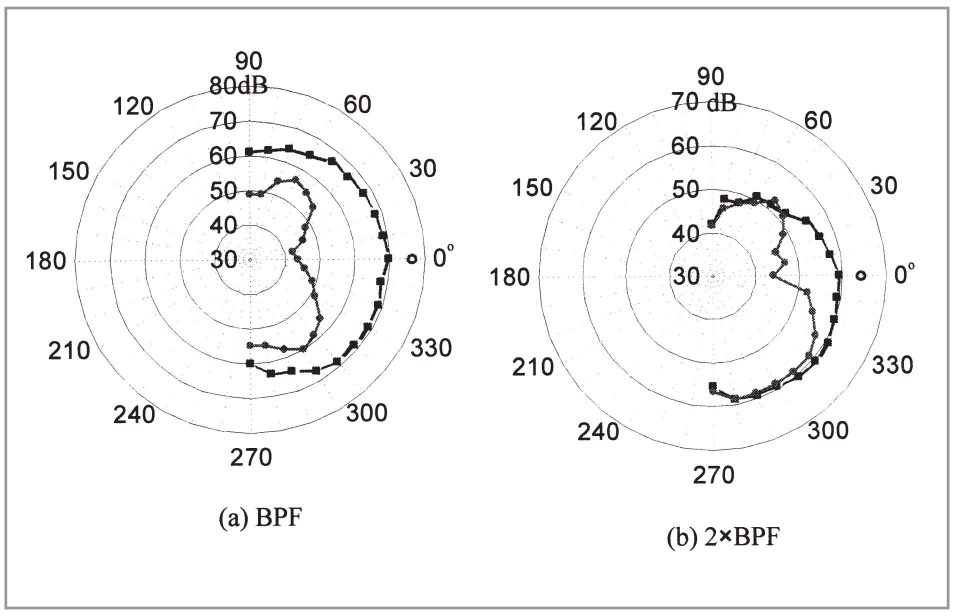


Figure 6. Measured downstream directivity of a 6-bladed (with equal pitches) automotive fan noise. Without control (■), with control (●). Error microphone at θ_0=0.

larger than 0.98 in all experiments conducted.

Finally, a HP 35665A spectrum analyser was used to measure the power spectra (20 averages for each measurement) at 19 regularly spaced monitoring microphone positions on a circular arc at 1.5 m from the fan centre, with $\varphi = 0$ and $-90^o < \theta < -90^o$ in the downstream half-space to evaluate the directivity of the primary (without control) and the resulting (with control) radiated sound field.

3.2. EXPERIMENTAL RESULTS

3.2.1. 6-bladed automotive fan with equal blade pitches

Fig. 5 shows the power spectrum of the sound pressure measured at the error microphone location ($\theta_0 = 0$) with and without active control. The tones at 1xBPF (300Hz) and 2xBPF (600 Hz) are decreased by 28 dB and 18 dB respectively at the error microphone location, and the residual sound field at these frequencies is essentially the broadband, uncorrelated noise.

The measured directivity without and with active control is shown in Fig. 6. The attenuations are maximal at the error microphone location ($\theta_0 = 0$). In Fig. 6.a, the directivity of the fan at the BPF is almost axially dipolar. The tonal noise is globally reduced and the directivity pattern after control is typical of the 2-lobed radiation in the error sensor half-space, as shown in Fig. 2.b.

The fan directivity at frequency 2xBPF (Fig. 6.b) is slightly shifted from the ideal axial dipolar case shown in Fig.3.a. However, the control is global in the error microphone half-space and the directivity under control also tends to be a 2-lobed radiation pattern, as shown in Fig. 3.a.

3.2.2. 7-bladed automotive fan with unequal blade pitches

Active control experiments have also been conducted for a fan with seven unequal blade pitches. Since, in this case, subharmonics of the BPF appear in the spectrum, more FIR coefficients must be chosen to control the additional tones, thus increasing the calculation load.

Fig.7 shows the power spectrum of the sound pressure measured at the error microphone location ($\theta_0 = \frac{\pi}{3}$) with and without active control. The tones at 1xBPF (340Hz), 2xBPF (680 Hz) and 3xBPF (1020 Hz) are decreased by 16 dB, 13 dB and 12 dB respectively at the error microphone location, and the residual sound field at these frequencies is essentially the broadband, uncorrelated noise. The sub-harmonics at 436 Hz, 772 Hz, 872 Hz and 968 Hz are also reduced down to the broadband noise level. The sub-harmonic at 918 Hz is decreased by 8 dB.

Fig. 8 shows the measured directivities without and with control, for the BPF and its first two harmonics. In Fig. 8.a, the directivity of the fan at the BPF is roughly dipolar and shifted from the ideal axial dipolar case. However, the tonal noise is globally reduced and the directivity pattern after control is typical of the 3-lobed radiation pattern shown in Fig. 2.b.

The fan directivity at frequency 2xBPF (680 Hz) shown in Fig. 8.b is also slightly shifted from the ideal axial dipolar case presented in Fig.3. However, the control is global in the error microphone half-space and the directivity under control tends to be a 3-lobed pattern, as shown in Fig. 3.a.

Finally, as anticipated in section 2, Fig. 8.c shows the more complicated directivity pattern of the fan at higher frequency (3xBPF-1020 Hz). In this case, the control with a single secondary source and a single error sensor is only effective close to the error microphone direction $\theta_0 = \frac{\pi}{3}$. Control spilloveer is noted in other directions. The control may be improved by using more error resulting in a more costly active control system.

4. CONCLUSIONS

For subsonic axial fans, global active control of the sound radiation can be achieved at the BPF and its first harmonic, using a single unbaffled loudspeaker and a single microphone in free field. At the error microphone, the sound pressure attenuation at BPF and its first harmonic are reduced to the broadband noise. At higher frequency, the acoustic directivity can deviate from the ideal axial directivity of the fan, which can lead to control spillover in directions far from the error microphone when the control is on. In this case, more error sensors would be required for the active control to be effective in the whole space.

As the secondary source is dipolar, the best control is achieved when the fan presents almost axially symmetric directivity patterns. Equalizing the number of struts and the number of blades (which is currently avoided in practice) could be used to obtain a fan mainly radiating an overall dipolar

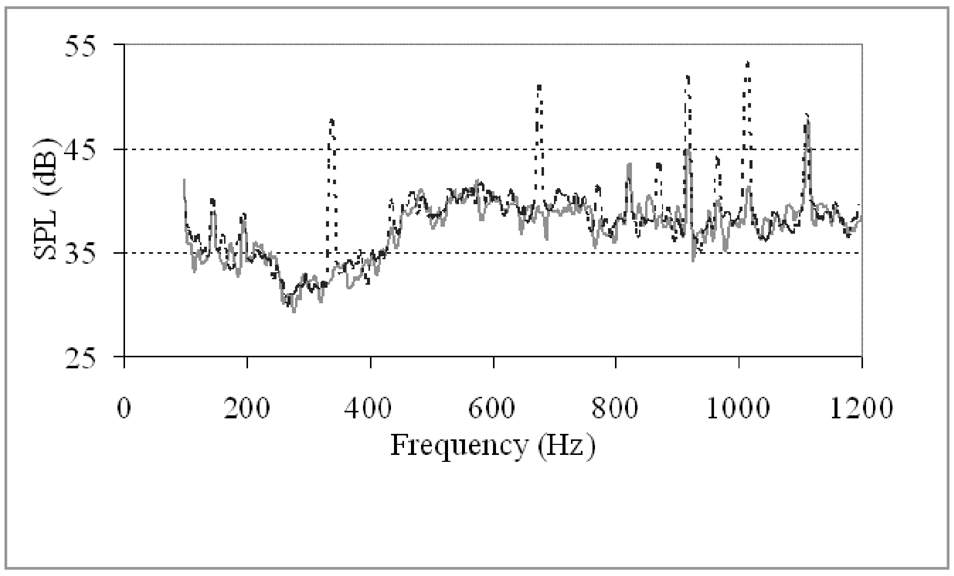


Figure 7. Power spectrum of the sound pressure at the error sensor position ($\theta_0 = \frac{\pi}{3}$) for a 7-bladed (with unequal blade pitches) automotive fan noise, with (solid line) and without (dashed line) active control.

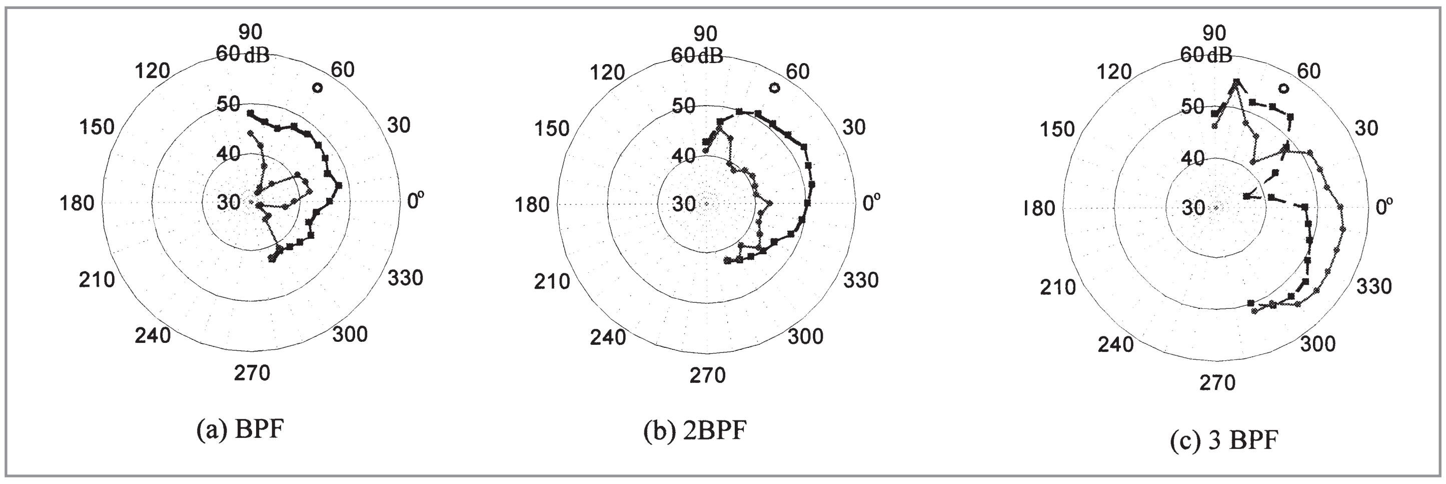


Figure 8. Measured downstream directivity of a 7-bladed (with unequal pitches) automotive fan noise. Without control (■), with control (●). Error microphone at $\theta_0 = \frac{\pi}{3}$.

sound, thus, resulting in maximal attenuation for the proposed active control configuration. In this case, the simplified fan noise model presented in Section 2 will precisely describe the directivity of the fan. Finally, using a rotor with equal blade pitches and identical blades results in fewer harmonics to be controlled. Therefore, less calculation load is required and the reference signal measurement is easier.

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SHOOTING DISTURBS LEARNING

A school has objected to a shooting range's bid for longer opening hours after the headteacher said pupils shouldn't be educated to the sound of gunfire. Hyndburn Council (Lancashire) has received over 60 letters of complaint on plans to extend the opening hours of a clay pigeon shooting range next to Holt Farm, Hermitage Street, Rishton. The site has been in operation for 35 years ad holds shoots between 11am and 2pm on Sundays. Owner Thomas Edward Threlfall is looking to expand and has applied for permission to hold sessions seven days a week. A council planning report says that the Sunday gunfire "is not a constant noise but rather a sharp impulsive noise that is unpredictable" and that increasing opening hours would have a detrimental impact on neighbours. Clayton-le-Moors' All Saints Primary School headteacher Peter Jump believes additional shoots would disrupt his pupil's education. He said: "We are due east of the site and its valley location means that the sound is amplified. "It isn't appropriate for school children to be listening to gunshots when they are trying to learn." Mr Jump has put his concerns in writing, along with 62 other residents. A further 30 people have signed a petition to prevent the changes. Residents in Clayton-le-Moors have complained that they are prisoners in their own homes during the summer shooting, saying it's like "living in a war zone". There are also concerns that the noise will scare wildlife.

SIREN MAKER TO BE SUED

US lawyers are rounding-up firefighters to sue Federal Signal Corp, an Illinois based company that makes sirens for fire engines. So far over 5000 firefighters have alleged that Federal Signal's sirens emit noise at levels which, in the words of one claim, 'are capable of causing permanent injury to human hearing.' The suit of one claimant, Carmelo Dejesus of Hackensach NJ, claimed that the manufacturer never warned him of the dangers and made no effort to rectify the defect. As a result, this fireman with 15 years service suffers from high-frequency hearing loss which will express itself as significantly limited hearing in later life. 'As he gets older, it will hit him harder and harder', said his attorney.

SYNAGOGUE BEATS COUNCIL

A rabbi accused of making too much noise at his synagogue has won a lengthy legal battle against a council which tried to gag him. A Muslim neighbour complained that her life was being made a misery by chanting, stamping and shouting from the building. Maryam Hafezji claimed she could not hear her TV and had to shout to make herself heard above the din. Rabbi Moshe Rottenberg was eventually found guilty of breaching a noise abatement order served on him. He was told to pay £4,000 costs and conditionally discharged. But when he appealed against his sentence, a crown court judge agreed the noise was infrequent and was not a nuisance - and overturned the magistrates court ruling. Hackney Council's noise officers did not give up, however. They went to the High court in a bid to have the earlier decision upheld. At the court yesterday, Mr Rottenberg's lawyers argued that the noise occurred only on holy days. They said the rabbi had run a religious school at the premises in Stamford Hill, North London, since 1982 - a year before Ms Hafezji moved into her home nearby. The school has 15 pupils and the building was blessed and turned into a synagogue in 1998. Simon Butler, for Hackney Council, claimed: 'There was evidence of jumping up and down on floorboards. There was chanting, there was wailing, there was shouting which on the officers' evidence interfered with conversation in the neighbouring property and you could not hear the TV. How can that be "mere irritation"? But Lord Justice Scott Baker, sitting with Mr Justice David Clarke, said the crown court judge was legally entitled not to follow the views of the environmental health officers, who were only witnesses. Planning experts said the judges had set an 'extraordinary' precedent which would alarm environmental health departments.