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APPLICATION OF FEEDFORWARD ADAPTIVE ACTIVE-NOISE CONTROL FOR REDUCING BLADE PASSING NOISE IN CENTRIFUGAL FANS

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This paper describes two configurations of feedforward adaptive active-noise control (ANC) technique for reducing blade passing noise in centrifugal fans. In one configuration, the control speaker is installed at the cut-off region of the fan, while in the other configuration at the exit duct. The proposed ANC system is based on the filtered-x least-mean-squares (FXLMS) algorithm with multi-sine synthesized reference signal and frequency counting and is implemented by using a digital signal processor (DSP). Experiments are carried out to evaluate the proposed system for reducing the noise at the blade passing frequency (BPF) and its harmonics at various flow speeds. The results of the experiment indicated that the ANC technique is effective in reducing the blade passing noise for two configurations by using the feedforward adaptive control.

1. INTRODUCTION

The noise generated by centrifugal fan falls into two categories. One is rotational blade passing noise with discrete or narrowband frequency components and the other is turbulent noise with broadband frequency spectrum. The noise generated by fan is usually caused by the fluctuating loads on the fan blades which results in a source of dipole order [1]. Many of the sources are near the trailing edge of blades or cut-off region of casing. An example result [2] of computation fluid dynamics for a centrifugal blower is shown in Figure 1. The fundamental mechanism of blade flow-acoustic interaction as a source of sound appears to be the development of an ordered train of vortices in shear layers produced in separating flows. The periodic vortices can excite resonance very easily to generate a sound field that influences the vortex sheet, which in turn produces a self-sustained oscillation at the cut-off region of casing.

Research on centrifugal noise reduction has been primarily focused on the control of blade passing noise. From a subjective point of view, tones are generally the most annoying components and thus need to be reduced. Many techniques, mostly passive means, have been developed for reducing the noise emitted by the fan [3, 4]. In 1987, Morinushi conducted experiments to investigate the influence of geometric parameters on noise and

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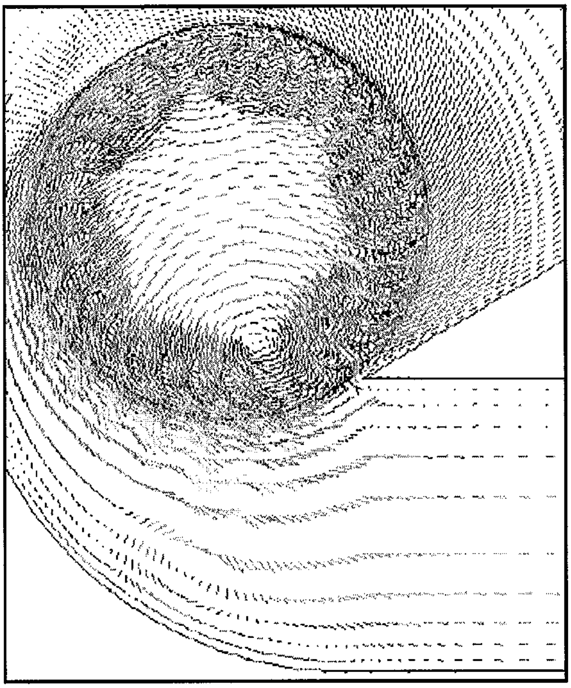

Figure 1. The simulation result of velocity field at the cut-off region of a centrifugal blower.

aerodynamic performance of forward curved centrifugal fans [5]. The results indicated that the cut-off clearance is an important factor for reducing the blade passing frequency. In 1980, Neise and Koopmann [6, 7] installed a quarter-wavelength acoustic resonator on the cut-off region for reducing blade-passing noise. Tuning of the resonator was achieved by changing the length via a movable end plug. In 1988, the same authors [8] also designed an active-noise control (ANC) systems with control speakers mounted at the cut-off region. In their design, single-frequency control is accomplished by using a manually adjusted phase shift unit.

Recently, ANC is being advanced rapidly in the last decade due to the progress of DSP technology. Many sophisticated control algorithms have been implemented on DSP platforms for practical applications [9]. In particular, ANC of duct noise has been extensively investigated both theoretically and experimentally. In the ANC structures to data, feedforward control has become most widely used for reducing duct noise, provided a non-acoustical reference is available. If, on the other hand, a non-acoustical reference is not available and control of discrete tonal noise is of interest, feedforward control remains a viable approach.

In the present study, two configurations for reducing noise from centrifugal fan using feedforward adaptive control are investigated. In one configuration, the control source is installed at the exit duct of a centrifugal fan, while in the other configuration at the cut-off region of the fan casing. To avoid undesired acoustic feedback, a synthetic reference scheme is employed in the filtered-x least-mean-squares (FXLMS) algorithm. In addition, multi-sine generator [10] and frequency counting techniques using fiber optical sensor are utilized for producing the synthetic reference so that fluctuations of blade speed can be better accommodated. The proposed ANC systems were implemented on a DSP and validated experimentally for various flow speeds. The results showed that the proposed

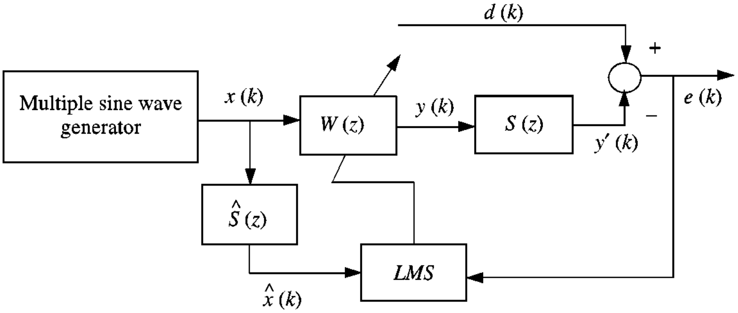

Figure 2. Adaptive feedforward control algorithm with synthetic reference input.

system was effective in suppressing blade passing noise and flow speed in an important factor of ANC performance.

2. DESIGN OF ANC SYSTEM AND CONTROLLER IMPLEMENTATION

The paper focuses on the ANC of periodic noises produced by fans. Because the fan noise generally contains tones at the BPF and its multiples, the FXLMS with a non-acoustical reference is employed such that undesired acoustic feedback from the control source to the reference microphone can be avoided. The block diagram of the FXLMS algorithm with synthetic reference [9] is depicted in Figure 2, where $W(z)$ is a FIR filter updated by the LMS algorithm, $d(k)$ is the primary noise and $\hat{S}(z)$ represents the estimated secondary path $S(z)$. The residual signal is expressed as

$$e(k) = d(k) - y'(k) = d(k) - s(k) * y(k) = d(k) - s(k) * [w^{\mathrm{T}}(k)\bar{x}(k)], \tag{1}$$

where $w(k) = [w_0(k)\, w_1(k) \ldots w_{L-1}(k)]^{\mathrm{T}}$ is the coefficient vector of $W(z)$, $\bar{x}(k) = [x(k)x(k-1)\ldots x(k-L+1)]^{\mathrm{T}}$ is the signal vector, and L is the order of filter $W(z)$. The most widely used method to minimize the instantaneous squared error $\hat{\xi}(k) = e^2(k)$ is LMS algorithm which updates the coefficient vector in the negative gradient direction with step size μ:

$$w(k+1) = w(k) - \frac{\mu}{2}\, \nabla\hat{\xi}(k) = w(k) + \mu\bar{x}'(k)e(k). \tag{2}$$

One problem generally arises in practical applications when BPF is used for generating the synthetic reference required by the FXLMS algorithm. The BPF is prone to fluctuations which significantly degrade the performance of attenuation by using the LMS-adaptive filtering. To alleviate this problem, a frequency counting technique in conjunction with a multi-sine generator is proposed in the paper to enhance the correlation between the noise and the reference.

The multi-sine generator used in the study is based on the result originally developed by Boyd [10]. Using his method, narrowband signals with very low-crest factors can be generated. In the context of the ANC application, this method is briefly reviewed as follows.

Consider a T-periodic signal u; the L^{∞} and L^2 norms are defined as

$$\| u \|_{\infty} \equiv \sup |u(t)| \tag{3}$$

and

$$\|u\|_2 \equiv \left(\frac{1}{T}\int_0^T (u(t))^2\,\mathrm{d}t\right)^{1/2}, \tag{4}$$

where $\|u\|_\infty$ is the peak of the signal u and $\|u\|_2$ is its root-mean-square (rms) value. The *crest factor* (CF) of a non-zero signal is defined as the ratio of its peak to rms value

$$CF(u) \equiv \frac{\|u\|_\infty}{\|u\|_2}. \tag{5}$$

It can be shown that the crest factor is always at least one, i.e., $CF(u) \geqslant 1$. Intuitively, the larger is CF, the more "impulsive" the signal.

Consider the multi-tone signal

$$u(t) = \sqrt{2N^{-1}} \sum_{k=N_0+1}^{N_0+N} \cos(kt + \delta_k), \tag{6}$$

where $N_0 \geqslant 0$. The Fourier coefficients of u satisfy

$$|\hat{u}_k|^2 = \begin{cases} 2N^{-1}, & N_0 < k \leqslant N_0 + N \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

Although the rms value of u is $\|u\|_2 = \sqrt{\frac{1}{2}\sum|\hat{u}_k|^2} = 1$, regardless of the phases δ_k, the peak changes dramatically with the phases. Instead of naively setting all δ_k to be zero, which would generally result in very large CF, we choose the Newman phases [11] to minimize the crest factor of u.

$$\delta_k^{(NEW)} = \frac{\pi(k-1)^2}{N}. \tag{8}$$

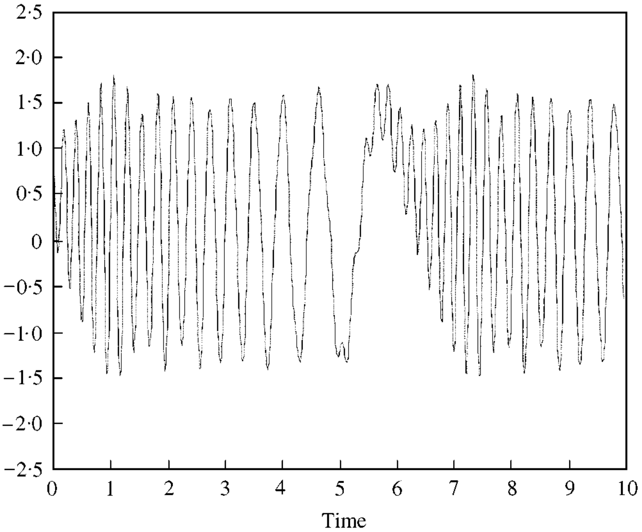

Figure 3. 32-tone Newman signal.

Numerical investigation shows that the crest factor of the Newman multi-tones

$$u_N^{(NEW)}(t) \equiv \sqrt{2N^{-1}} \sum_{k=1}^{N} \cos((k + N_0)t + \delta_k^{(NEW)}) \tag{9}$$

is very small (approximately 4·6 dB) for moderate N. Figure 3 shows the 32-tone Newman multi-tone. Note the curious resemblance to a swept frequency signal.

In the implementation of FXLMS algorithm, the reference signal is preferably less impulsive (low CF). We thus choose Newman multi-tone signal as the synthesis reference because it shows the desirable property. In equation (9), the term $\cos((k + N_0)t + \delta_k^{(NEW)})$ when implemented in the DSP program is suggested to be decomposed into $\cos((k + N_0)t) \cos \delta_k^{(NEW)} - \sin((k + N_0)t) \sin \delta_k^{(NEW)}$ for better numerical stability.

In the paper, the BPF of blower is fluctuating about the center frequency 323 Hz within a 6 Hz band. The sound pressure spectrum measured at the error microphone is shown in Figure 4. In order to measure a more accurate BPF for generating the reference signal, an optical fibre sensor is used. The output signal of the sensor is a series of square pulses (0–0·9 V), as shown in Figure 5. The principle of frequency counting is simply to count (by sample) the time interval between two rising edges of the pulses. When a rising edge occurs, the counter is started to increment for each program cycle until the next rising

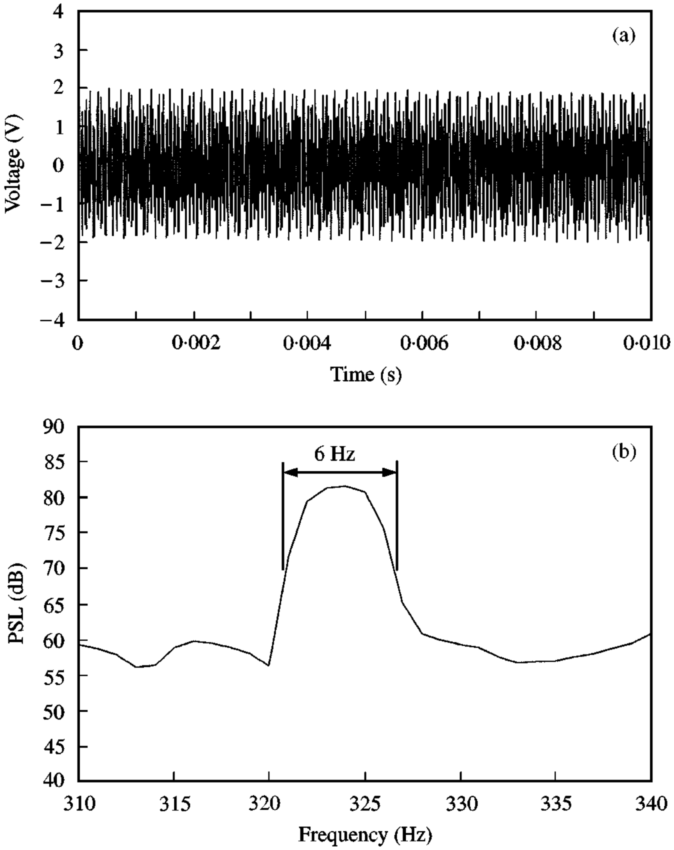

Figure 4. The blade passing noise measured in error microphone. (a) Time domain; (b) frequency domain.

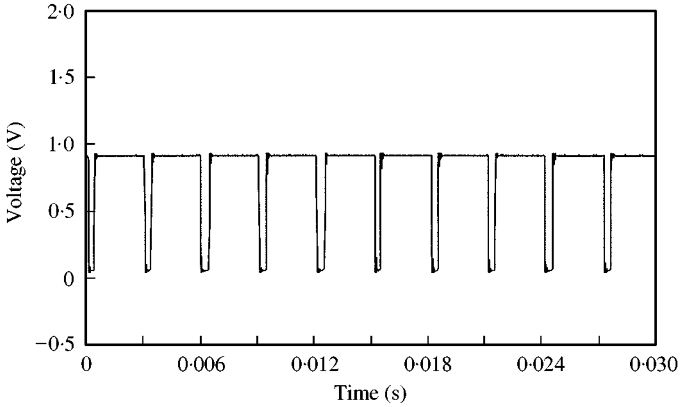

Figure 5. Time domain signal of the fiber optical sensor.

edge. The count value N is then stored and the counter is reset. The BPF can be obtained from

$$f = \frac{1}{NT}, \tag{10}$$

where T is the DSP sampling period. The advantage of this approach is that the sensor can reflect a more accurate BPF better, which may be slightly fluctuating due to unknown reasons, which is typical in practical systems.

3. EXPERIMENTAL VERIFICATION

In the paper, the adaptive feedforward ANC system is applied to reduce BPF noises in two configurations. The first configuration is a ducted centrifugal blower, where the control speakers are mounted at the mid-span of the exit duct [12]. The second configuration is an identical centrifugal blower with a control speaker mounted at the cut-off region. Both configurations are experimentally investigated under different flow conditions using the aforementioned ANC technique. The control system is implemented by using a 60 MHz floating-point TMS320C32 digital signal processor equipped with two 16-bit analog IO channels. The experimental cases are summarized in Table 1.

3.1. ADAPTIVE ANC WITH CONTROL SOURCE MOUNTED AT EXIT DUCT

The complete experimental arrangement of ANC system of the ducted blower, including the digital controller, the signal conditioning circuit, the sensor and the actuator, is schematically shown in Figure 6. The impellers of the centrifugal fan are six backward curved blades of tip diameter 150 mm. A duct made of plywood is used in the experiment. The length of the duct is 600 cm and the cross-section is 20 cm × 20 cm. The sampling frequency is chosen to be 4 kHz considering the cut-off frequency of the duct (870 Hz). In this study, the noise radiated outside the upstream of the duct is neglected.

As a preliminary test of the ANC system, a loudspeaker serverd as the primary source to generate periodic noise. The result of the experiment indicated that the feedforward adaptive ANC controller achieved up to 30 and 20 dB noise reductions in 330 and 660 Hz respectively. In the second experiment, the primary loudspeaker is replaced with a practical

TABLE 1

BPF noise and its harmonic noise attenuation at various flow speed

	Control at exit duct (dB)		Control at cut-off region (dB)	
Flow speed (m/s)	BPF	2 × BPF	BPF	2 × BPF
0	30	20	25	13
0·25	13	8	7	6
0·3	13	6	5·5	4
0·35	12	5	5	3
0·4	12	5	4	3
0·45	12	5	4	3
0·5	11	4·5	3	2

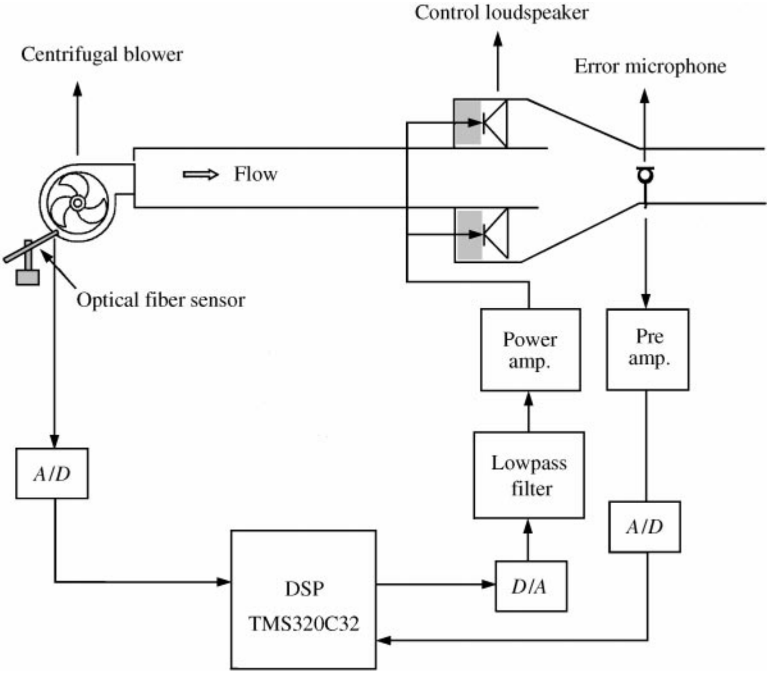

Figure 6. The experimental set-up of the duct ANC system.

source, a centrifugal blower (with rotating frequency of 3300 rpm and flow speed of 0·25 m/s). The result of the experiment indicated that the ANC system attained 13 and 8 dB noise reductions at the BPF and 2 × BPF, respectively, as shown in Figure 7 and Table 1.

In order to examine the effect of flow on the ANC system, the flow speed is varied from 0·25 to 0·5 m/s. The performance of noise attenuation for various flow speed is also summarized in Table 1. The results indicated that the flow indeed had adverse effect on the ANC performance. This also confirms the conclusion in a previous work [13] that perturbation of the plant (the secondary path) due to flow could affect the performance, even the stability of an ANC system.

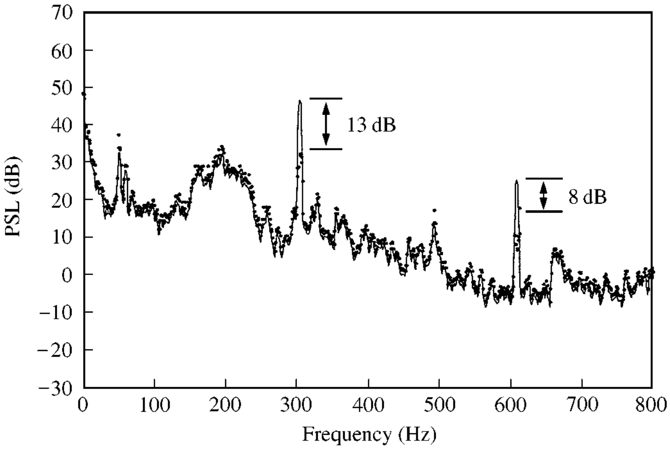

Figure 7. The experimental result of the duct ANC system at flow speed 0·25 m/s. ——, control off; – – –, control on.

3.2. ADAPTIVE ANC WITH CONTROL SOURCE MOUNTED AT CUT-OFF REGION

In some applications, space is of major concern and the aforementioned ANC configuration using a duct becomes impractical. For such cases, an alternative but more compact configuration using a control source mounted at the cut-off region of the fan is investigated in the paper. The control speaker is connected to the fan through an adapter (diameter is 50 mm, length is 80 mm). The interface between the adapter and the fan casing is a perforated screen covered with 3 mm diameter holes which amounts to 20% open area. The distance between the error microphone and the exit of the fan is 30 mm.

To verify the control algorithm, a preliminary test was conducted by using three loudspeakers mounted around circumference of the casing for simulating the harmonic BPF noise. The experimental set-up is shown in Figure 8. The periodic signal is generated from a function generator. The ANC results using this synthetic primary source showed 25 and 13 dB noise reductions at the BPF and 2 × BPF, respectively, as shown in Figure 9 and Table 1.

Next, the centrifugal fan is practically opened with rotating frequency 3300 rpm and flow speed 0·25 m/s. The experimental set-up is shown in Figure 10. A fiber optical sensor is utilized to detect the rotation speed of the blower. The frequency counting technique described previously is applied in this experiment. In order to accelerate the speed of convergence in FXLMS algorithms, scaling was used in the computation.

In the case of practical fan source, signal quality was considerably degraded by the turbulence noise. To alleviate the problem, microphone windscreen can be used. However, a better approach was employed in this paper as shown in Figure 11. A 5 mm capacitor microphone was embedded in a streamline nose cone. A small slit tube was cut from the tip of the cone to the microphone cavity. This kind of error microphone configuration is particularly useful in the applications where high-speed flow is present.

The experimental results of Figure 12 for the practical fan show that approximately 7 dB reduction at the BPF (330 Hz) and 6 dB reduction at 2 × BPF (660 Hz) were achieved when the flow speed is 0·25 m/s. Significant degradation of performance can be observed for the practical source with flow condition, where system properties have been perturbed from the nominal one for which the secondary path is identified. To further explore the effect of flow on the ANC performance, the ANC system is applied to cases with various flow speeds

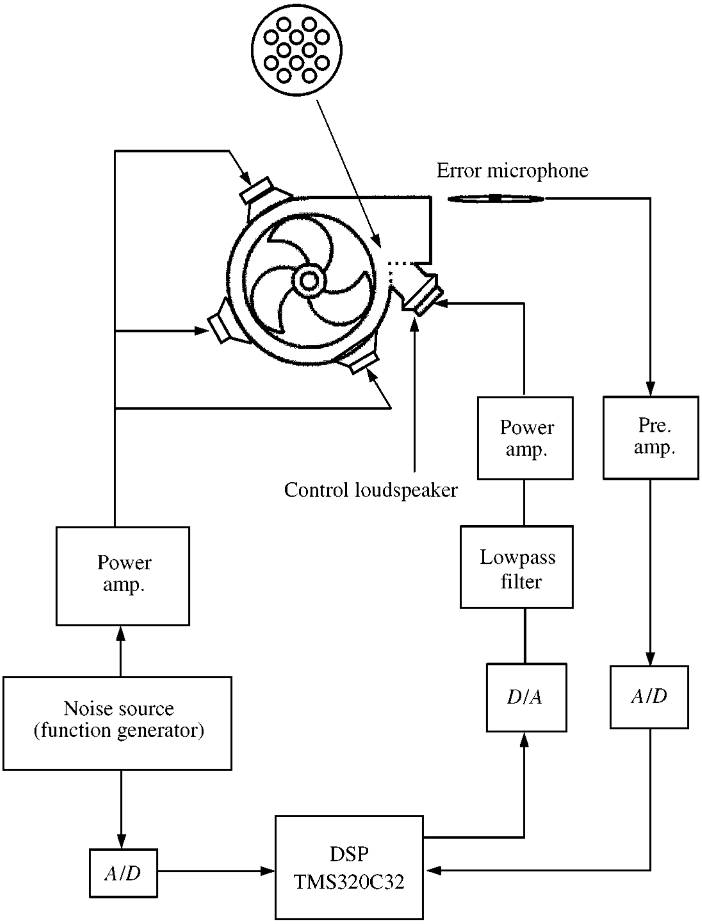

Figure 8. The experimental arrangement of the ANC system with control source mounted at cut-off region. Synthetic noise generated by speakers serves as the primary source.

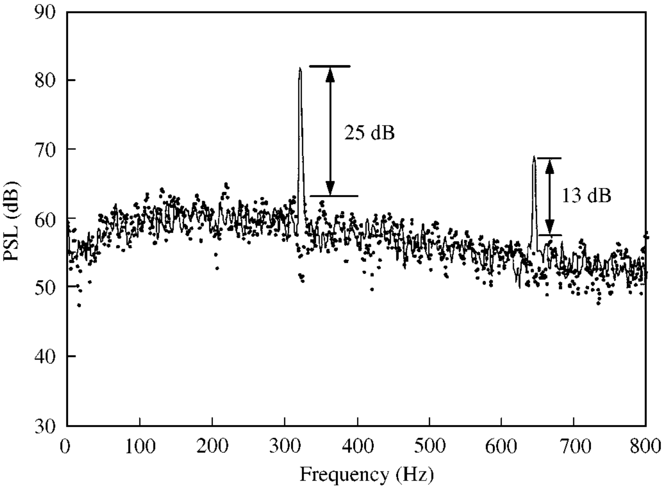

Figure 9. The experimental results of the ANC system with control source mounted at cut-off region. Synthetic noise generated by speakers serves as the primary source. ——, control off; – – –, control on.

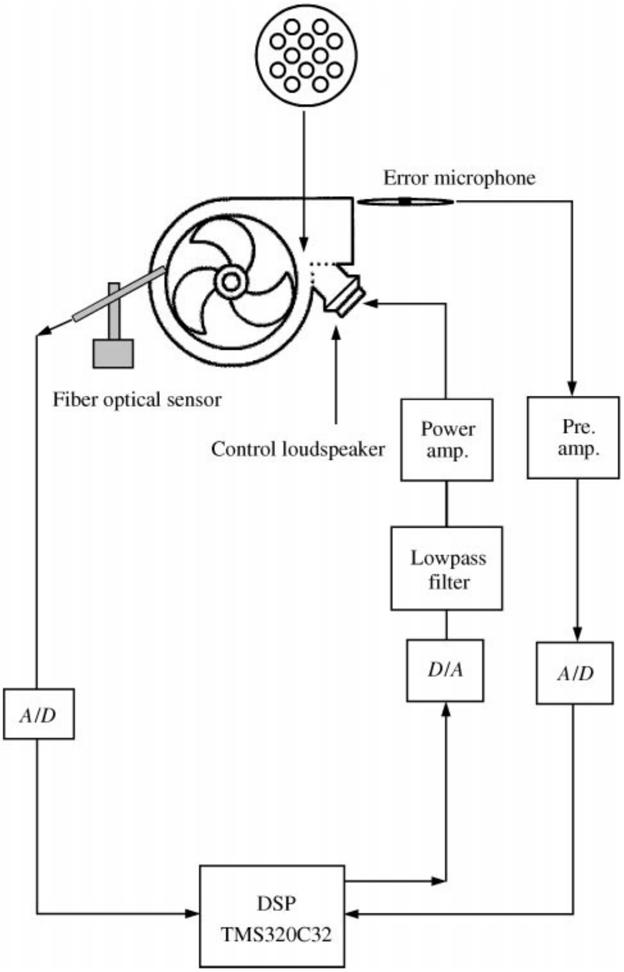

Figure 10. The experimental arrangement of the ANC system with control source mounted at cut-off region. Practical fan noise serves as the primary source.

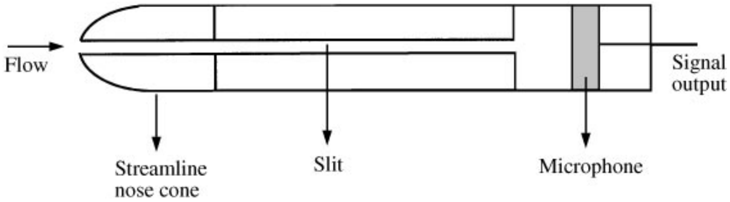

Figure 11. Capacitor microphone with a streamline nose cone.

(from 0·25 to 0·5 m/s). The results are also summarized in Table 1. It is evident that the higher is the flow speed, the lower the noise reduction.

4. CONCLUSIONS

Two configurations of feedforward adaptive ANC technique for reducing BPF noise in centrifugal fans are investigated in this paper. The ANC system is based on the FXLMS

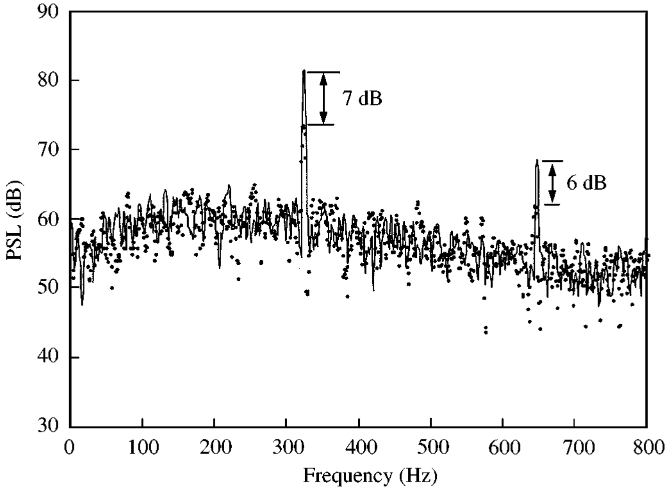

Figure 12. The experimental arrangement of the ANC system with control source mounted at cut-off region. Practical fan noise serves as the primary source. The flow speed is 0·25 m/s. ——, control off; - - -, control on.

algorithm with multi-sine reference and frequency counting method. The system is implemented by using a DSP platform. Experiments are carried out to evaluate the proposed system for reducing the noise at the BPF and is harmonics at various flow speeds. The results of experiment indicated that the feedforward adaptive ANC system is effective in reducing the tonal noise by using both configurations. In particular, the ANC system with a control source mounted at the cut-off region achieved up to 25 dB attenuation for a synthetic noise generated by a speaker and 6–7 dB reduction for the practical fan at the BPF. Although the performance of this configuration is not good as the ducted fan, it provides a useful alternative for reducing BPF noise when the space is a critical issue in the application of interest.

The effect of flow on ANC performance is examined. Plant uncertainty (air flow in the case) is one of the contributing factors that could affect the performance as well as the stability of control systems. Future work will be focused on the development of a more robust adaptive controller to accommodate perturbations and plant uncertainties in the practical applications.

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