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Session 1pEAa: Active and Passive Control of Fan Noise

1pEAa1. Active control of axial and centrifugal fan noise

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Both axial and centrifugal fans are used to cool information technology (IT) equipment. These fans generate noise that can be annoying to their users, particularly the tonal noise that can be radiated. Work has focused on developing a method to attenuate the tonal noise associated with both of these types of fans. A compact system is used, whereby control sources are placed in close proximity to the fan. A genetic algorithm has been implemented to determine optimal source configurations. The attenuation associated with some configurations is found to be much more sensitive to error than others. For a given configuration, by using a relatively simple point source model it becomes possible to identify optimal near-field error sensor locations, which results in a compact noise control solution that provides significant global attenuation of the radiated tonal noise. This paper will review progress that has been made to apply this method to both axial and centrifugal fans. Experimental results confirm that it is feasible to achieve significant global control using this method.

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1. INTRODUCTION

Small axial and centrifugal cooling fans are routinely used with information technology (IT) equipment to provide cooling. However, these fans also generate acoustic noise which can be annoying to users. Active noise control (ANC) is a potential solution for this problem that has been investigated for a number of years. Early studies by Quinlan,[1] Lauchle *et al,.*[2] and Wu[3] were followed by more recent efforts by Gee and Sommerfeldt,[4,5] Homma *et al*.,[6] and Wang and Huang.[7] One desirable feature of an ANC solution for fan noise would be to have the control sources and error sensors located in close proximity to the fan, so that a compact solution results. Work over a number of years in the Acoustics Research Group at Brigham Young University has focused on developing such solutions. In this paper, we provide a broad overview of developments in this area, along with a number of lessons learned and challenges that yet remain.

2. GLOBAL ANC OF FAN NOISE

A. Cooling Fan Noise and Source Coupling

Axial and centrifugal cooling fans are used in numerous applications with IT equipment, appliances, and so forth. These fans vary in size and operating conditions, but the noise radiated from them can be characterized with two components – a shaped broadband spectrum associated with the turbulent airflow, and one or more harmonics of the blade passage frequency (BPF) that are superposed on the broadband noise. For the work presented here, we have focused on attenuation of the tonal noise from these fans, as they are typically more annoying than the broadband noise. When these fans are mounted in casings, as they typically are, it has been found that the fan directivity is monopole-like in nature for the lowest harmonics of the BPF.[8] Based on this result, it has been determined that the radiation from a small axial or centrifugal fan can be modeled as a monopole source. This concept leads to the possibility of utilizing source coupling to achieve the desired global control of the fan noise.

In order to achieve significant global attenuation of the radiated fan noise, it is necessary to achieve acoustical source coupling between the fan and the control sources used, which leads to the formation of a higher order acoustic source that radiates less efficiently. This coupling occurs as the spacing between the primary source and secondary source(s) is small, relative to a wavelength. When this condition exists, the radiation of one source affects the radiation impedance of the other source, and vice versa. Nelson and Elliott[9,10] review in detail this principle of mutual coupling and show how an appropriate selection of control source strengths and locations can result in a reduction of radiated power by the primary and control sources.

A. Adaptive Control System

The ANC control system that we have developed for use in attenuating fan noise is based on the multi-channel filtered-x least-mean-squares algorithm[11] implemented on a Texas Instruments (TI) TMS320VC33 DSP processor, with a custom input/output (I/O) board. Multiple error microphones, placed in the near field of the fan were implemented, along with multiple miniature control speakers, also placed in the near field. The BPF and harmonics controlled were generally all below about 2 kHz, so a typical sampling frequency used was around 4 kHz.

To eliminate the acoustic feedback path from control sources to reference sensor, a non-acoustic reference sensor was chosen. In many cases, the fans provided a tach signal which could be used for the reference sensor. When such a tach signal was not available, an infrared emitter/detector pair was mounted on either side of the fan blades, resulting in a pulse train whose fundamental frequency matched the BPF. In both cases the pulse train obtained was lowpass filtered to avoid aliasing and limit the number of harmonics present to the BPF and typically two or three higher harmonics.

Because our ANC system is based on near-field error sensors, these sensors can sometimes be subjected to significant low-frequency flow-induced noise. Although this noise often appears well below the BPF, its greater levels can result in clipping at the analog input stage of the DSP board. Consequently, error signals are bandpass filtered prior to the DSP; a highpass filter eliminates the bulk of the flow-induced noise below the BPF and a lowpass filter minimizes any potential aliasing effects in the controller.

3. RESULTS OF ANC RESEARCH

Prior research has focused on a number of topics related to controlling the noise from axial and centrifugal fans. These topics include: studies of optimal control source configurations, determining optimal error sensor locations, sensitivity of error sensor locations, and control of centrifugal fans mounted in enclosed (laptop) cases.

A. Control Source Configurations

In order to achieve global attenuation of the fan noise, it is necessary to achieve mutual coupling between the fan and the control sources. Thus, the desired control source configuration needs to be investigated to determine how many control sources to use, and where to place those sources. The work of Gee and Sommerfeldt[4,5] utilized the source coupling theory described by Nelson and Elliott[9,10] to determine good source configurations. For this work, the fan and control loudspeakers were all modeled as point sources. Gee and Sommerfeldt confirmed that the power reduction possible increased for a given source configuration as the source separation distance relative to the wavelength decreased, which suggests that the sources should be located as close to the fan as physically possible. Figure 1 shows the maximum attenuation that can be achieved for a given number of sources mounted to surround the fan in the same plane as the fan is located. For these results, all sources are placed to surround the fan and are equidistant from the center of the fan. The attenuation is shown as a function of *kd*, where *k* is the acoustic wavenumber, and *d* is the physical distance between the center of the fan and the center of a loudspeaker. It can be seen that significant improvement is achieved as one goes from a single control source to two control sources and then three control sources. However, little improvement is achieved by increasing the number of sources beyond three, a result that was confirmed experimentally by Monson *et al.*[12]

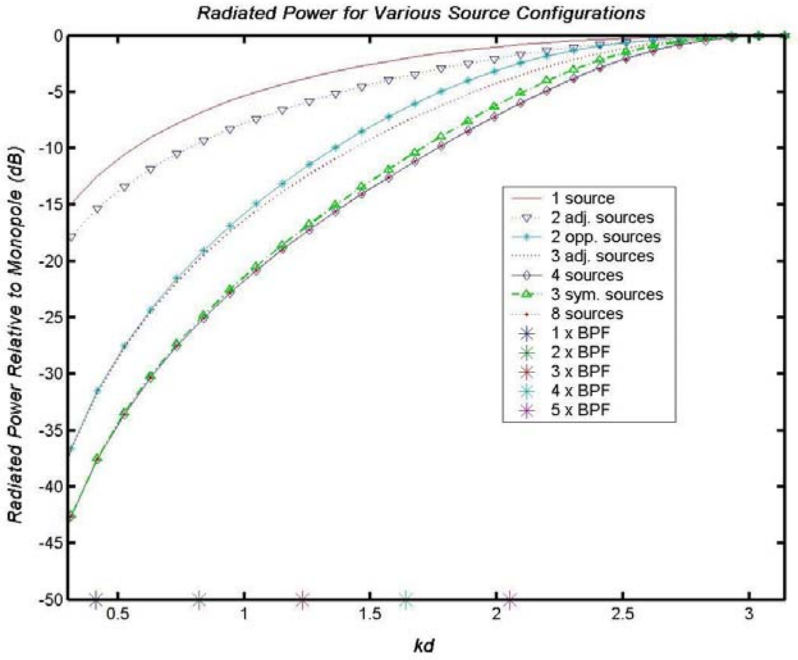

FIGURE 1. Radiated power as a function of *kd* for various control source configurations. Note that the four and eight source results essentially overlay each other. Adjacent (adj.) sources are 90° apart, the other sources represent symmetric arrangements. The asterisks are the *kd* for the harmonics of that particular fan's BPF.

While these results indicate the maximum attenuation that can be achieved for a given control source configuration that places the multiple sources symmetrically around the fan, it does not necessarily indicate the optimal configuration, in terms of achieving maximum possible sound power reduction for a given number of control sources. Duke *et al.*[13] used a genetic algorithm to explore the optimal placement of control sources for a given number of sources, and found that the maximum theoretical sound power reduction is generally not obtained by placing the sources in a symmetric configuration. Rather, the maximum attenuation comes from placing the control sources in a line, with the primary source in the center. Figure 2 shows the two arrangements of the control sources when four sources are used, while Figure 3 indicates the maximum sound attenuation that can be achieved.

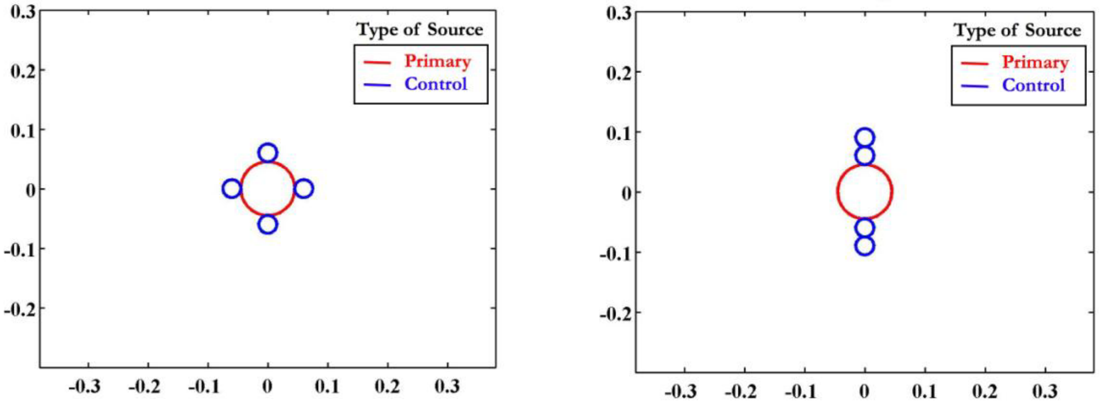

FIGURE 2. Symmetric (left) and linear (right) control source arrangements.

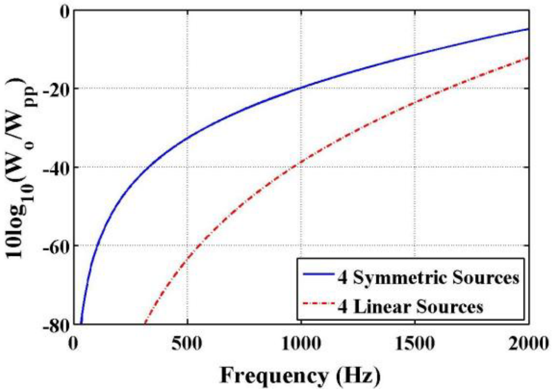

FIGURE 3. Sound power levels relative to the primary monopole as a function of frequency for the symmetric and linear source configurations in Fig. 2.

In practice, it was found experimentally that it was significantly more difficult to experimentally achieve the predicted sound attenuation for the linear configuration that for the symmetric configuration. Further study revealed that the linear configuration is much more sensitive than the symmetric configuration to errors in error sensor placement, as will be shown in the next section. As a result, the symmetric configuration has been shown to generally be much more robust in performance than the linear configuration.

B. Error Sensor Configurations

Conventional approaches to ANC have generally implemented error sensors located in the far field, at least partially because it has been suggested that the use of near-field sensors could be problematic.[14] However, for the application of cooling fans, it is generally not practical to place the error sensors in the far field of the fan. Thus, earlier research focused on identifying a robust scheme for placing error sensors in the near field in a manner that leads to global attenuation. This led to an ANC approach that in fact, successfully uses near field error sensors in a manner that leads to the desired global attenuation of the fan noise. The approach relies on the source coupling work outlined by Nelson and Elliott.[8,9]

As shown in the previous section, Nelson and Elliott outlined how the minimum power output of a given source configuration can be determined by identifying the optimal source strengths of each control source that leads to minimum power. After obtaining this solution, which relies on modeling the fan and the control sources as point sources, the radiated *pressure* field associated with the solution that minimizes radiated sound power can be plotted in the near field. It has been shown that the optimal location for an error sensor is one that results in the greatest attenuation of the primary noise source's radiation.[14] Thus, a plot of the power-minimized near-field pressure relative to the pressure field of the primary source alone reveals ideal error sensor locations for a given source configuration and frequency. Figure 4 shows an example plot of this sound-power-minimized near-field pressure level normalized by the primary source field for four symmetrically oriented loudspeakers surrounding the fan. The bright spots indicate the locations of the sources, and the dark null represents a large attenuation in the near field of the fan when the sound power is minimized, which corresponds to ideal locations for the error sensors. The shape of this null has been found to be frequency dependent, but the frequency dependence is weak, and there are regions on this null curve that change very little with frequency. Thus, the error sensors were placed at those locations that corresponded to nulls at all frequencies of interest.

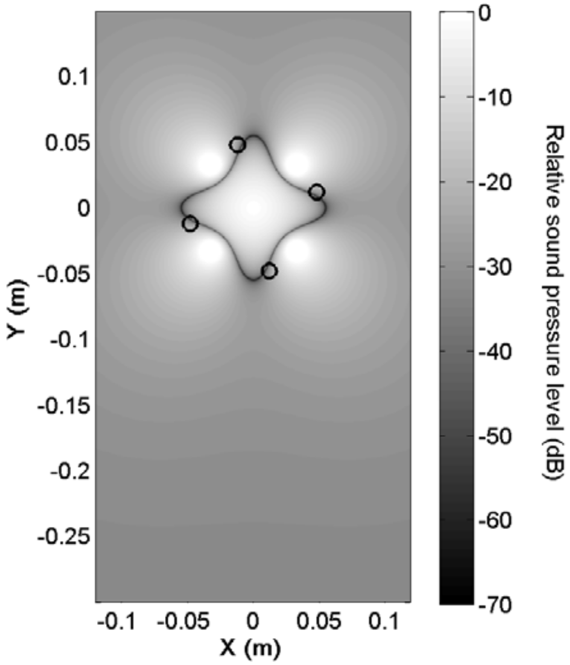

FIGURE 4. Sound pressure levels, relative to the primary pressure field alone, in the plane of the control sources. The circles represent actual error sensor placement for an experiment described in Ref. 12.

Figure 5 provides an example of the attenuation achieved using this symmetric configuration of four control sources. In this figure, the radius wireframe mesh corresponds to the sound level of the fan radiation in a particular direction, while the radius (and color) of the solid surface corresponds to the sound level of the radiation in that direction.

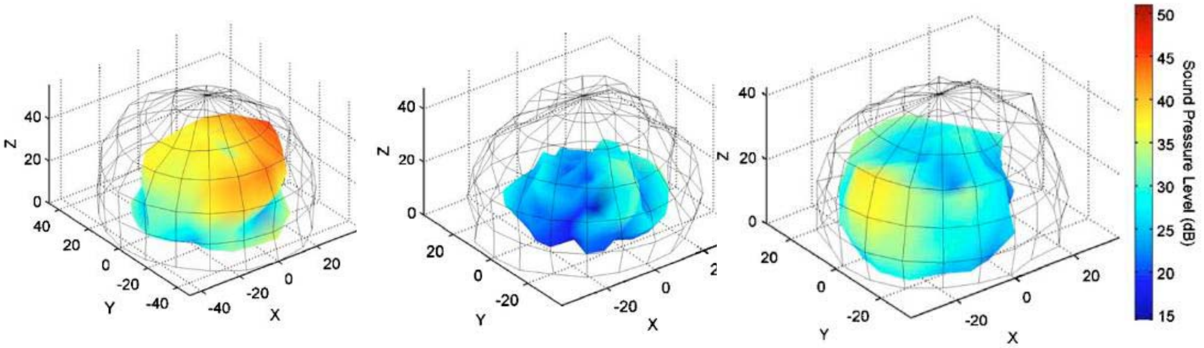

FIGURE 5. Control at the first three harmonics of the BPF (600 Hz) for a 60mm cooling fan. The wireframe mesh represents the fan radiation without ANC.

Experimental results have been obtained for various source configurations, including the symmetric and linear configurations. It was found that it was much more difficult to achieve the predicted attenuations when using a linear configuration, which led to a study of the robustness of that configuration, particularly with respect to errors in sensor locations.[15] This research revealed that even small errors in the placement of one or more of the error sensors at optimal locations can quickly reduce the attenuation achieved when implementing the linear configuration. The symmetric configuration, on the other hand, is rather robust to these placement errors, as can be seen in Figure 6. In this figure, “far linear mic” represents an error for a microphone located on the nodal line located between the two outer control sources, while “near linear mic” represents an error for a microphone located on the nodal line located between the fan and the adjacent control sources.

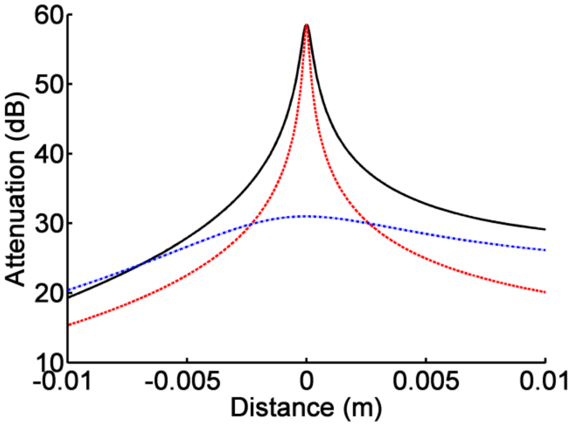

FIGURE 6. The simulated sound power attenuation (in decibels) for three simulations. Position error is introduced for one microphone, while keeping the other microphones stationary at optimal locations, with the abscissa being the distance from the optimal microphone position.

C. Control of Centrifugal Fans

For applications such as laptop or notebook computers, centrifugal fans (blowers) are typically utilized for cooling, rather than axial fans such as is often used for desktop computers. Some of our past research has focused on attenuating the sound radiated from these blowers.

For this application, the same principle can be used as was used with axial fans, but with some modification. For the axial fans, the fans were radiating to the exterior of the casing, so a model of free-space radiation was used to determine source and sensor configurations. For a laptop computer, the blower is mounted in a way that it radiates externally, but also into the laptop enclosure. It was determined that the amount of acoustic energy radiated through the interior of the laptop and subsequently out various ports was nominally equal to the amount of energy radiated directly to the exterior from the blower. As a result, it is necessary to consider both the exterior radiation and the interior radiation from the fan if one wishes to achieve significant attenuation of the fan noise radiated.

To account for both radiation paths, two models were developed and coupled together. The first model treated the fan as a point source radiating to the exterior and determined the source and sensor configuration in much the same was as was done for axial fans. For preliminary work to check this model, the laptop enclosure was place in a baffle in such a manner as to isolate any noise radiated through the interior of the laptop enclosure from the fan noise radiated directly out from the blower. A second model was developed that again treated the blower as a point source located inside the laptop enclosure. This model incorporated a simple model of the interior of the enclosure, along with same losses to account for the loss of acoustic energy through the ports and vents of the enclosure. Using this model, it was again found that after numerically minimizing the radiated power based on this model, near-field nodal lines resulted that were deemed to be the optimal locations to place the error sensors for attenuating the noise radiated through the interior. This model was also checked experimentally by separating the noise radiating through the interior and exterior by means of a baffle. For both models developed, the sources and sensors were placed adjacent to the blower, as close as possible and in the locations determined through the modeling procedure. This was done in an effort to develop a solution that would be very compact in nature. The usefulness of the models was also tested by moving one or more of the error sensors away from the locations determined to be optimal by the models. When this was done, a significant degradation in performance was generally observed, thereby giving confidence that the model was useful in predicting configurations that provide significant attenuation of the fan noise.

After developing both models, the two models were run in two implementations: as two independent control systems, and as a fully coupled system. It was found that the fully coupled system (which accounted for radiation from the internal control system out the blower and for radiation from the external control system through the interior of the enclosure) resulted in somewhat better performance, with the improvement in the overall global attenuation typically being on the order of a couple of decibels. Figure 7 shows one result obtained for global attenuation of the BPF of 981.5 Hz. It can be seen that the overall attenuation of 16.1 dB is global in nature. As part of these tests, the reduction at the standard operator position was also monitored, and was found to be nearly the same as the overall attenuation (15.8 dB for this result).

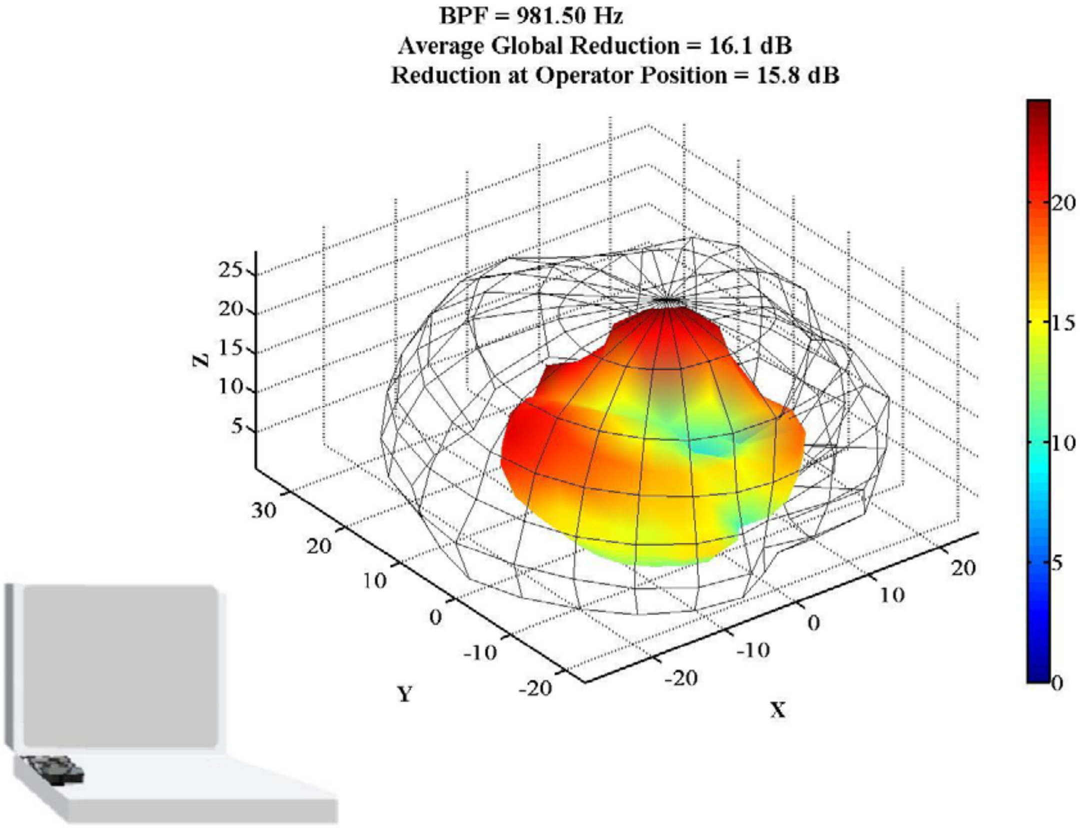

FIGURE 7. Global attenuation of the fan noise radiated from a laptop enclosure using two coupled control systems designed to attenuation the exterior and interior noise. The results shown are for the BPF (981.5 Hz), and the laptop icon shows the orientation of the laptop to the measured results. Global attenuation of 16.1 dB was obtained, with attenuation at the standard operator position of 15.8 dB.

4. RESULTS OF ANC RESEARCH

Work on attenuating the noise radiated from small axial and centrifugal fans has focused on developing a compact solution with control sources and error sensors located in the extreme near-field of the fan. The approach has been based on developing a simple model of the radiation and placing the sources and sensors based on the results of those models. While it may be argued that the models do not capture all of the details of the radiation, it has been found for many applications that the models capture enough of the associated radiation mechanisms so as to make them very useful in guiding the design of the control system. Experimental results have consistently provided significant global attenuation that have at least qualitatively matched the numerical predictions, and in a number of cases have provided a rather good quantitative match between prediction and experiment.

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