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Global active control of axial cooling fan noise: An overview of past and present research

Kent L. Gee[a]
Scott D. Sommerfeldt[b]
Department of Physics and Astronomy
Brigham Young University
N-283 ESC
Provo, UT 84602

ABSTRACT

During the past eight years, researchers at Brigham Young University have been engaged in a pragmatic effort to actively reduce the noise radiation from small axial cooling fan noise. The first of a series of studies on the subject demonstrated that a feedforward, multichannel controller with near-field error sensors was successful in globally reducing four harmonics of the blade passage frequency. Additional studies have revealed optimal locations for both error sensors and control sources and have further reduced the spatial footprint of the system actuators. Other issues, such as the impact of a reverberant enclosure on control and the use of feedback control to reduce the broadband noise have been looked at, but are the subject of ongoing investigations.

1. INTRODUCTION

Active noise control (ANC) of the acoustic emissions of small axial cooling fans is a problem that has seen appreciable research effort since about 1990. 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] The work of Gee and Sommerfeldt, which dealt with the development of a compact, near-field control solution, spawned a number of other related studies in the Acoustics Research Group at Brigham Young University. In this paper, we provide a broad perspective of fan noise reduction research at BYU in terms of lessons learned and challenges—both technical and practical—that yet remain.

2. GLOBAL ANC OF FAN NOISE

A. Cooling Fan Noise

Although axial cooling fans used in appliances or electronic hardware come in a wide range of sizes and with differing numbers of blades and support stators, the noise may be characterized by one or more harmonics of the blade passage frequency (BPF) that rise above a shaped broadband spectrum (e.g., see Fig. 1). Lauchle *et al.*[2] showed that typical unbaffled fans behaved primarily like a dipole at the BPF but exhibited more complicated behavior at two and three times the BPF. The directivity of a fan that is baffled or mounted in an enclosure, however, is more monopole-like, even for harmonics of the BPF. The three-dimensional directivity of an enclosure-mounted fan at the BPF and subsequent three harmonics is shown in Fig. 2, where it can be seen the fan's radiation becomes more directional at higher frequencies.

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[a] Email address: kentgee@byu.edu
[b] Email address: scott_sommerfeldt@byu.edu

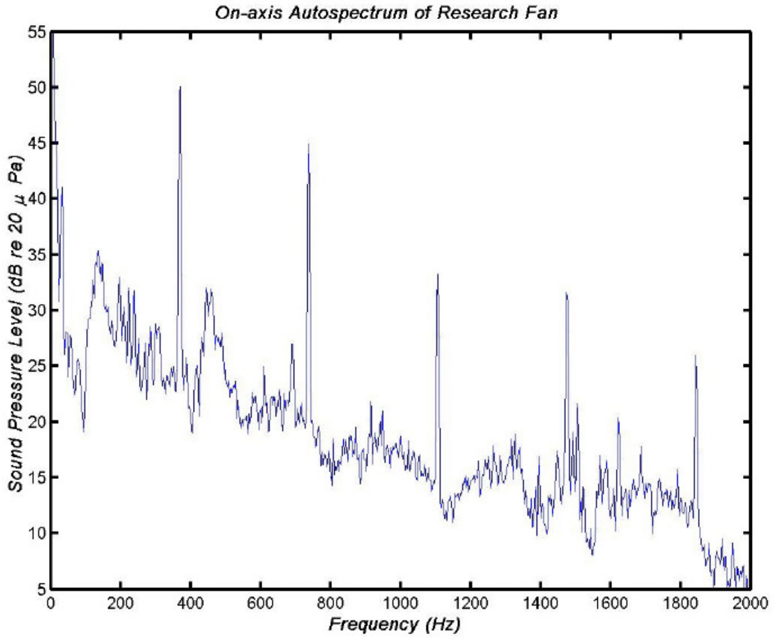

Figure 1: On-axis spectrum measured on an 80-mm axial cooling fan.

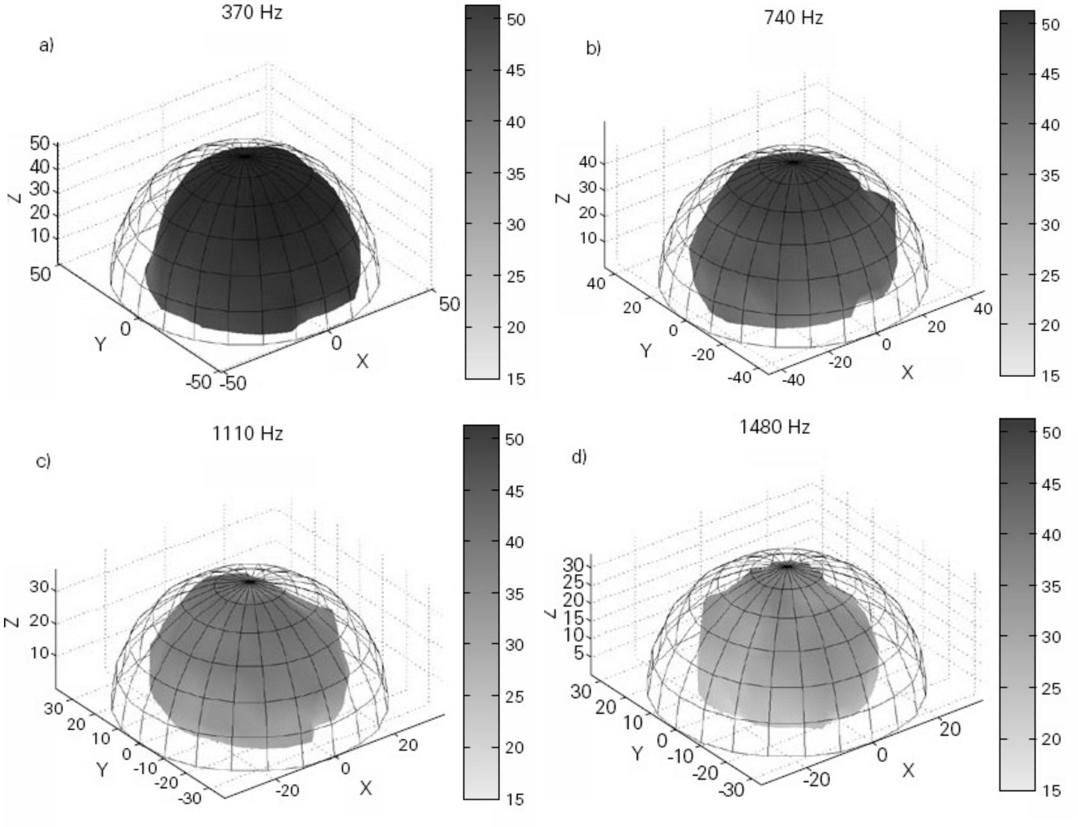

Figure 2: Three-dimensional directivity for the first four harmonics of the blade passage frequency (370 Hz). The color and radius of the surface represent sound pressure level, whereas the hemispherical wireframe helps to show relative omnidirectionality.

B. Principle of Source Coupling

Significant global reduction of radiated power from a primary noise source (i.e., the fan) requires that it acoustically couple with the control sources, thereby creating a higher-order acoustic source. To acoustically couple, the separation distance between the primary and control sources must be small relative to a wavelength. When the sources are close relative to a wavelength, the radiation of one source affects the radiation impedance of the other source, and vice versa, thereby changing the total radiation of the system of sources. This principle of mutual coupling, described by Nelson and Elliott,[8,9] shows that an appropriate selection of control source strengths can result in a reduction in system (primary and control sources) radiated power.

C. Adaptive Feedforward Control System

When targeting tonal noise from a fan, the ANC controller we use is based on a multi-channel filtered-x least-mean-squares algorithm (e.g. see Ref. 10) implemented on a Texas Instruments TMS320C6713 digital signal processor (DSP) with typical sampling frequencies of around 4 kHz. Although we have sometimes used online system identification based on Ref. 11 to provide estimates of the secondary path transfer functions, most of our work has been performed with offline system identification because of the relative invariance of the control scenario.

To eliminate the feedback path between the secondary (control) sources and the reference sensor, we have chosen to use a non-acoustic reference sensor. For fans without a tach signal, the sensor is an infrared emitter/detector pair mounted on either side of the fan blade that provides a pulse train whose period is equal to the inverse of the BPF and that contains the harmonics to be controlled. For fans with a tach signal, which usually triggers twice per revolution, we use analog frequency-multiply and divide electronics to yield a pulse train at the BPF. A lowpass filter is used in both cases to limit the number of harmonics present in the reference signal and prevent aliasing before the signal is digitized for use in the controller.

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 entering 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 PRIOR RESEARCH

The results of prior fan-related ANC research at BYU are grouped here into three classes: control-source-related studies, error-sensor-related studies, and “additional” studies. Principal findings in these three areas are discussed in turn.

A. Studies of Control Sources

The work of Gee and Sommerfeldt[4,5] built on the source coupling theory described by Nelson and Elliott.[8,9] By modeling the fan and control loudspeakers 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 a wavelength decreased. They deemed it desirable to impose a constraint that the control loudspeakers be mounted in the same enclosure panel as the fan and, consequently, investigated a number of two-dimensional source configurations not previously investigated. Since they surrounded their fan with four symmetrically oriented loudspeakers, they investigated combinations of those loudspeakers, as well as two other cases, three and eight symmetrically arranged loudspeakers. The sound power reduction achievable is shown in Fig. 3 as a function of *kd*, where *k* is the wave number and *d* is the physical distance between the center of the fan and the center of a loudspeaker. For two and three loudspeakers, they showed that symmetrically oriented sources theoretically outperformed adjacent sources. In addition, their theoretical results showed that increasing the number of symmetrically oriented sources beyond three provided little additional benefit in terms of possible sound power reduction. This was experimentally confirmed by Monson *et al.*[12] The studies of Gee and Sommerfeldt[4,5] and Monson *et al.*[12] contain three-dimensional directivity plots of the fan radiation with and without ANC for multiple harmonics of the BPF. One such set of plots is shown in Fig. 4**,** for which the sound power reduction was 14.5, 16.6, and 9.0 dB for the first 3 harmonics.

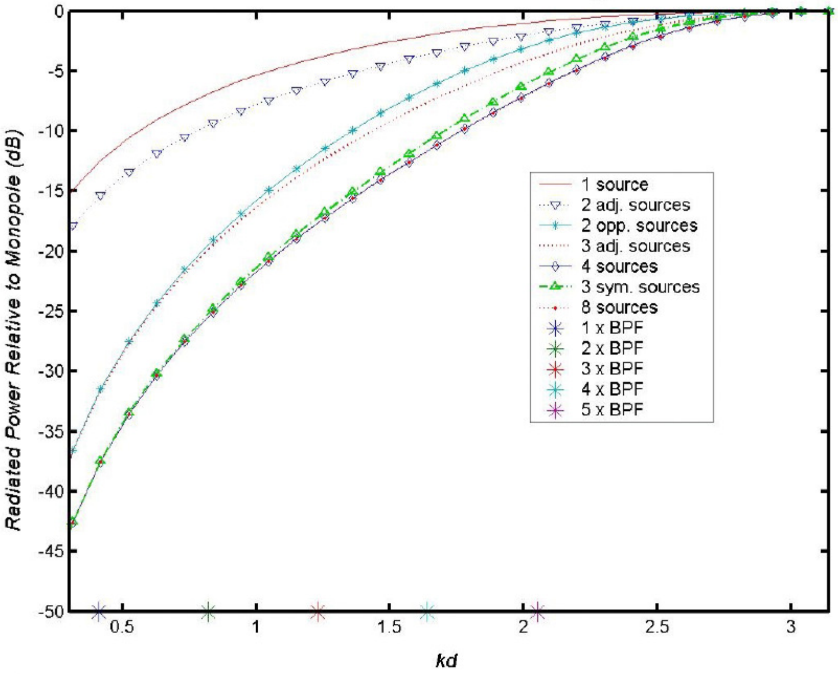

Figure 3: Radiated power as a function of *kd* for various control source configurations. Note that the four and eight source results essentially overlay each other. Adjacent (adj.) sources are 90° apart, the other sources represent symmetric arrangements. The asterisks are the *kd* for the harmonics of that particular fan's BPF.

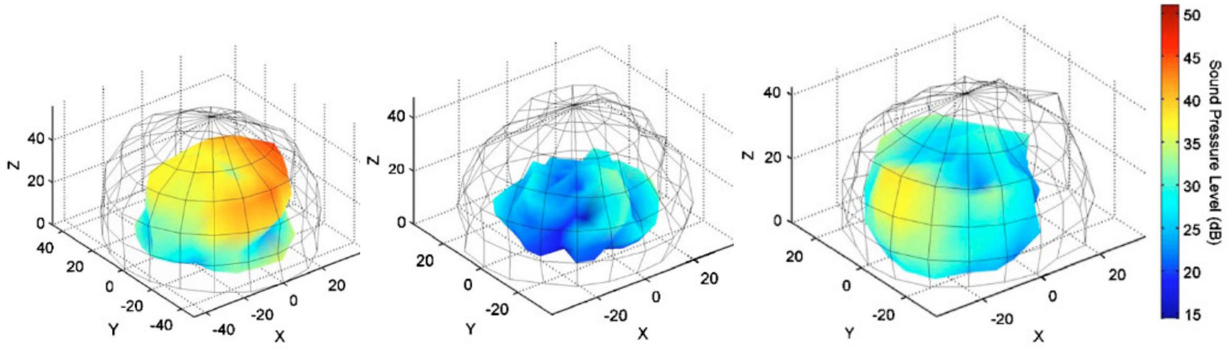

Figure 4: Control at the first three harmonics of the BPF (600 Hz) for a 60mm cooling fan. The wireframe mesh represents the fan radiation without ANC.

Despite the fact that multiple harmonics were controlled using symmetrically oriented loudspeakers, Gee and Sommerfeldt and Monson *et al*. did not investigate whether this was the optimal source arrangement. Here, "optimal" signifies maximum sound power reduction possible for a fixed number of loudspeakers and physically realizable separation distances. Duke *et al*.[13] studied optimal placement of control sources through the use of a genetic algorithm. They discovered and experimentally confirmed that although intuition may suggest that maximum sound power reduction should be achieved by symmetrically surrounding the source in two or three dimensions, this is not, in fact, the optimal source configuration. Duke *et al*. found that the optimal source configuration was to place all the control sources in a line with the primary source in the center. This arrangement, shown in Fig. 5, resulted in higher-order multipole radiation characteristics than the symmetrically oriented case and, consequently, significantly greater achievable sound power attenuation as shown in Fig. 6. Practical drawbacks to this line-source arrangement include a possibly inconvenient spatial footprint of the system and greater sound power requirements of the loudspeakers used.

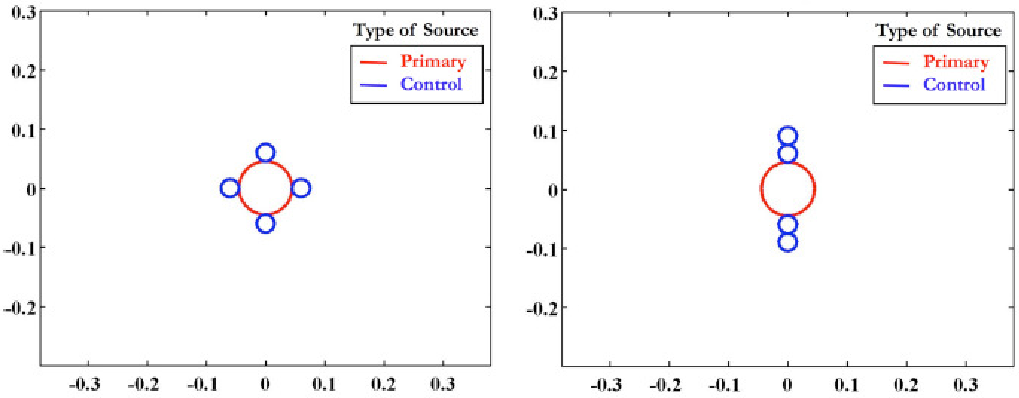

Figure 5: Symmetric (left) and linear (right) control source arrangements.

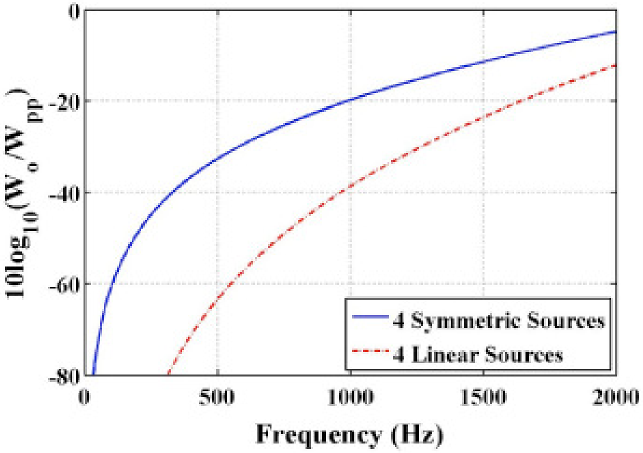

Figure 6: Sound power levels relative to the primary monopole as a function of frequency for the symmetric and linear source configurations in Fig. 5.

B. Studies of Error Sensors

One of the important system design considerations at the outset of the fan noise research at BYU was the locations of the error sensors. Although prior research with global ANC suggested that far-field reductions required far-field sensors (e.g., see Ref. 14), this approach would not be practical for typical cooling fan installations. Furthermore, "good" error sensor locations are often discovered in individual ANC applications by trial and error. Consequently, it was decided that a robust scheme for near-field error sensor placement was needed that would result in significant far-field sound power reductions. One study by Gee and Sommerfeldt[4] demonstrated with several trials for different control source configurations that near-field error sensors could, in fact, be successfully used to achieve significant sound power reductions. The authors further showed[5] that some microphone locations in the near field should be better than others by extending the work of Nelson and Elliott.

Nelson and Elliott[8,9] previously demonstrated how the minimum power output of a given system of sources could be determined by finding optimal source strengths of each control source. With this information in hand, the radiated *pressure* field for this power-minimized set of sources can be plotted in the near field. By recognizing that the optimal location for an error sensor is the one that results in the greatest attenuation of the primary noise source's radiation,[14] a plot of the power-minimized near field relative to the primary-source-alone near field reveals ideal error sensor locations for a given source configuration and frequency. An example plot of the sound-power-minimized near-field pressure levels normalized by the primary source field is shown in Fig. 7 for three symmetrically oriented loudspeakers surrounding the fan. The dark null represents large attenuation in the near field of the fan when the sound power is minimized; consequently the error microphones should be placed so as to create these nulls in practice. The circles represent actual microphone locations selected, which resulted in significant sound power reductions for three harmonics of the BPF.

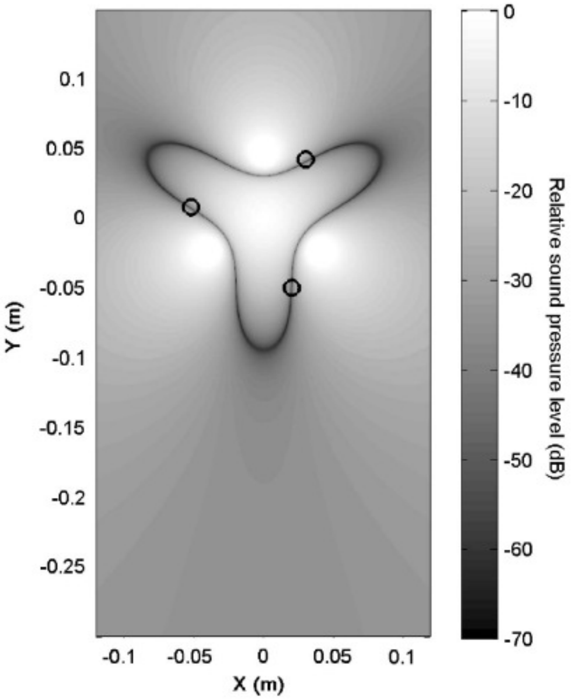

Figure 7: Sound pressure levels, relative to the primary pressure field alone, in the plane of the control sources. The circles represent actual error sensor placement for an experiment described in Ref. 12.

The work by Gee and Sommerfeldt[5] showed that placement of the error microphones along theoretically predicted locations results in, on average, greater global reductions in the far-field than randomly arranging the microphones in the near field. However, they did not confirm that placement of the microphones along the theoretically predicted nulls resulted an acoustic near field that was similar to the sound-power-minimized near field. A detailed near-field measurement would further demonstrate that this process by which microphone locations were determined was indeed founded on solid physical reasoning. Consequently, Shafer *et al.*[15] constructed a linear array of 0.635-mm Type 1 microphones (see Fig. 8) and performed some detailed near-field measurements for various ANC configurations with both a loudspeaker and a fan as a primary source. They found that for the microphones in the predicted optimal locations, the experimentally achieved and predicted near fields were similar (see Fig. 9). Furthermore, when multiple microphones were moved outside the theoretically predicted regions (as shown at the right in Fig. 9), the near-field was dramatically altered and the sound power reduction provided by the ANC system was reduced from 17.1 dB to 9.0 dB.

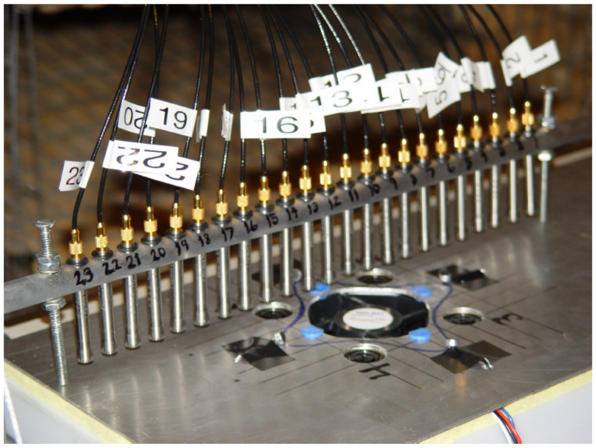

Figure 8: Linear array of 23 Type-1 GRAS microphones.

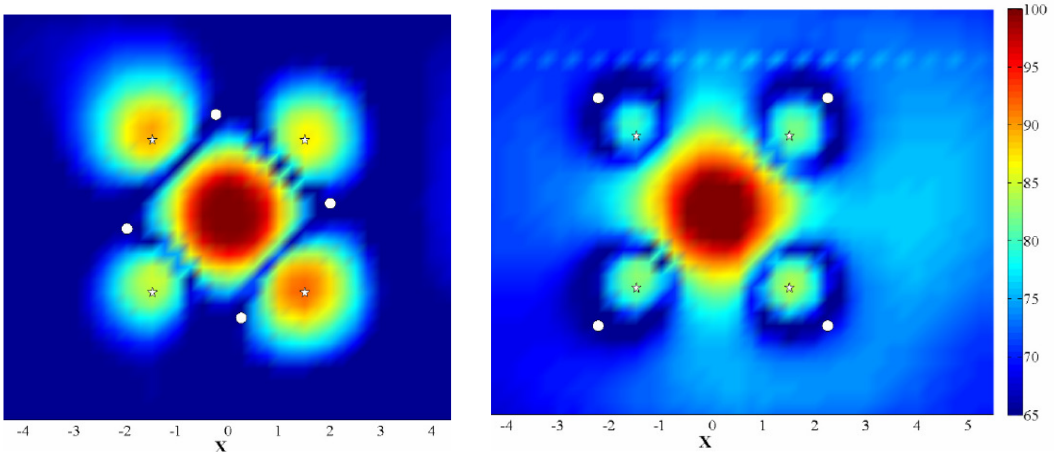

Figure 9: Near-field sound pressure level map 12.7 mm above the source plane for a loudspeaker primary source. The circles represent error sensor locations. Left: Microphones along the theoretically predicted nodal line. Right: Microphones in different near-field locations.

C. Additional Studies

There has been a number of other fan ANC-related studies that have yielded additional information about both the physical situation and the practicality of implementation for a variety of fans. Monson[16] placed the fan setup in a reverberation chamber and showed that similar sound power reductions could be achieved without altering the error sensor locations from those predicted according to free-field conditions. Monson *et al.*[12] also showed that the ANC hardware could fit with a 60-mm fan within a 80mm x 80mm footprint, thus providing the possibility of retrofitting existing hardware with a smaller, ANC-quieted fan running at a higher speed. Another study conducted by Shafer[17] looked at modeling the fan not as a monopole, but as a multipole, in order to further optimize error sensor placement particularly at higher harmonics of the BPF. Although the results of the investigation showed that the multipole-predicted near field matched the experimentally measured near field without ANC, greater sound power reductions were achieved than were predicted via the multipole arrangement. Assuming the multipole model is a valid reconstruction of the source properties, this should not be theoretically possible. Consequently, the issue is being looked at further.

Two other studies merit mention here. First, Duke[18] used particle image velocimetry and other flow visualization techniques to investigate the flow field incident on near-field error microphones. He found that the flow induced noise at the error microphones was not usually caused by the direct exhaust from the fan, but rather from entrained air moving across the chassis toward the fan flow. However, the noise caused by the airflow had minimal impact on ANC system performance and, consequently, flush mounting of the error sensors was not required. He also found that the introduction of ANC had negligible effect on the airfield itself. The other study, carried out by Duke *et al.*,[19] studied in detail the ability to use the tach signal from the fan as a non-acoustic reference signal. They found that fluctuations in BPF were tracked well by the changes in the tach signal frequency for each fan tested and for different values in back pressure.

4. DIRECTIONS FOR FUTURE RESEARCH

The fan-related ANC research at BYU has largely addressed the reduction of tonal noise from small cooling fans and showed that not only can it be significant and global, but it can also be compactly and practically implemented. With the tonal component of the noise largely eliminated, a natural extension is to now target the broadband component of the noise. Green *et al.*[20] performed initial work in this area with a digital feedback controller, but found that the latency of the DSP system used greatly reduced the overall attenuation possible. Additional research in this area is forthcoming. Another research area that needs to be addressed is the issue of multiple fans in a server-type application. Questions include: how can multiple fans, which will have at least slightly different BPFs, be best controlled? What is the appropriate source and error sensor arrangement? Should a different variant of the filtered-x LMS algorithm be implemented? A final area being considered is that of interior-mounted cooling fans. The research to date has largely focused on externally mounted cooling fans. However, many applications, such as CPU or video card cooling fans are mounted inside the chassis. How can the noise from these fans best be reduced? These questions raised here serve as current and future directions for axial fan ANC research at BYU.

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