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Multi-channel Active Control of Axial Cooling Fan Noise

Kent L. Gee and Scott D. Sommerfeldt
Brigham Young University, Department of Physics, N-283 ESC
Provo, Utah 84602, USA

Abstract

A multi-channel active control system has been applied to the reduction of free-field tonal noise from a small axial cooling fan, typical of those used in office equipment and other technology. The experimental apparatus consists of an aluminum enclosure which houses the fan, an infrared detector-emitter pair which serves as a reference sensor, loudspeakers, microphones, and appropriate filters and amplifiers. The control signals are generated using a multi-channel filtered-x algorithm. Potential near-field error microphone locations have been investigated by modeling the research fan and loudspeakers as point sources to obtain a mathematical expression for radiated power. The minimization of this power has yielded likely microphone locations in the extreme near-field and has also guided the number and location of control sources. Experiments with various control configurations have shown that multiple control channels are required for significant global attenuation of higher harmonics of the research fan's blade passage frequency (BPF). In addition, there are predictable near-field locations which consistently lead to significant reductions in the global mean-squared pressure for the first four harmonics of the BPF. For example, a four channel configuration results in global mean-squared pressure reductions of 9-19 dB for each of the four harmonics.

1. Introduction

Small axial-flow fans are used to cool computers, projectors, copiers, and other related technology, preventing too much heat from building up and causing damage to the devices. The noise they produce contributes to background noise levels in the workplace and classroom, causing annoyance and disrupting concentration. The noise emitted from these fans is composed of both broadband and tonal radiation. The tones may rise as much as 25-30 dB above broadband levels, and therefore typically dominate a cooling fan's overall spectrum. Because of this, tonal noise radiated from cooling fans has been extensively studied and its physical generating mechanisms are fairly well understood [1].

Tonal noise in axial cooling fans radiates as harmonics of the blade passage frequency (BPF), which is calculated by multiplying the number of fan blades by the shaft speed in revolutions per second. It is principally caused by spatially variant loading on the blades which results in unsteady forces on the fan's rotor. This nonuniform loading is usually attributed to obstructions such as finger guards, wires, or fan supports located closely to the fan which disrupt the airflow into or out of the fan. The rotating blades' periodic interaction with these obstructions results in the generation of the BPF and harmonics. The number and relative levels of the BPF harmonics present are dependent on the nature of the obstructions and the shape of the blades.

Because of the preeminence of the tonal noise in the fan's spectrum, much research has been carried out on its reduction. An ever-present demand for the reduction in size of technology makes passive innovations difficult because of the clearance required for clean inflow conditions. Furthermore, the safety requirement for finger guards on computers and other technology will always be a source of tonal noise because of the spatially variant loading imposed on the blades by the guard. Over the past decade or so, the concept of using active noise control (ANC) to reduce cooling fan tonal noise has been investigated. Although few cooling fan ANC studies have been carried out, some fundamental progress has been made in the area, demonstrating an ability to significantly attenuate the fan's BPF and harmonics at the error microphone, but less ability to achieve global reductions, especially for higher harmonics [2,3,4].

The research presented in this paper comprises the use of multi-channel ANC to globally attenuate the first several harmonics of a cooling fan's BPF. In addition, the results of an analytical analysis designed to determine appropriate near-field error microphone locations that would maximize global tonal attenuation are summarized and experimental results described.

2. Theoretical Analysis

One of the challenges associated with ANC implementation in a three-dimensional sound field is the selection of error microphone locations for a given control source configuration that will result in global attenuations. An additional requirement of any practical cooling fan ANC system is that the error microphones be located in or on the equipment enclosure and very likely in the acoustical near-field. Finally, these locations would have to be consistent from unit to unit to enable mass production and make the system cost effective. The challenge, therefore, is to determine near-field locations which will result in consistent global attenuations. In cases where the dimensions of both the noise and control sources are much less than the wavelength of the sound radiated, the determination of appropriate sensor locations may sometimes be guided by representing the sources as point source models. A mathematical expression for the coupled sources' radiated power with arbitrary source strengths can then be obtained. Differentiating the power expression with respect to each of the source strengths' magnitudes and phases, setting each of the derivatives equal to zero, and solving the resultant series of equations yields the source strengths that minimize the total power radiated from the configuration of sources [5].

Because the dimensions of typical cooling fans are much less than the wavelength of at least its BPF, this analysis was applied to a fan with various control source configurations to determine their optimal source strengths. With this accomplished, the magnitude of the pressure radiated from each of the source configurations was plotted in the plane containing the noise and control sources, in order to examine their near-field behavior. Plots for the pressure radiated at 370 Hz for two and four control sources, each at a distance of 6 cm from the fan are shown in Figure 1. Each configuration shows a null along which the acoustic radiation is minimal, suggesting that if the error microphones were placed such as to drive the pressure to a minimum there, the global power reduction would be maximized. Of special interest is the four secondary source configuration in Figure 1b, which exhibits a closed null connecting the four control sources. This suggests an appropriate near-field location for the error microphones that would minimize the power.

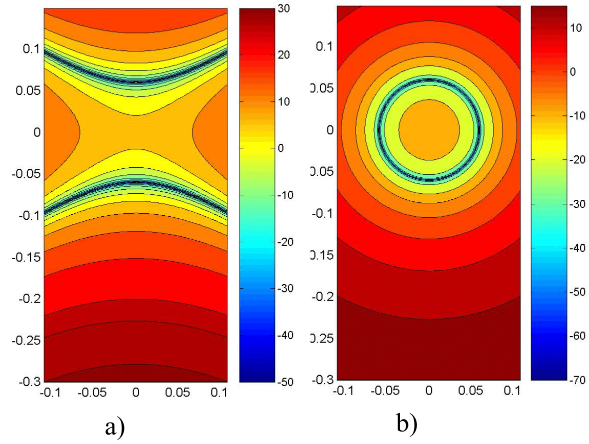

Figure 1. Radiated pressure, in dB, of source configurations with power-minimized source strengths, with the primary source at the origin. a) Two control sources, at (0,.06) and (0,-.06). b) Four control sources, at (0,.06), (0,-.06), (.06,0), and (-.06,0).

Another aspect of the theoretical analysis carried out dealt with determining the maximum number of sources necessary to minimize the radiated power. The analysis demonstrated that three symmetrically placed sources performed almost as well as the four source configuration, with negligible difference for the first three harmonics of the BPF. Also established was the fact that for a source separation distance less than one-half wavelength, there was essentially no difference in power reduction for the four symmetric sources shown in Figure 1b than for eight sources placed at 45 degree angles around the primary source. Because of these results, four control sources were chosen for the experiments performed in order to be able to easily test multiple source configurations.

3. Experimental Setup

The fan chosen for the tests was a 3.25", seven-bladed Mechatronics fan, which had a BPF of 370 Hz when mounted in the top of a 9"x18"x16" aluminum enclosure. A 1" wide strip of aluminum was placed near the inlet of the fan in order to create spatially unsteady flow conditions. A small, inexpensive infrared emitter-detector pair placed on either side of the fan blades was chosen as the reference sensor and its signal, a nominal square wave, was lowpass filtered to only contain the first four harmonics of the BPF. The control sources selected were 28 mm diameter loudspeakers and were mounted at equal angles around the fan, with the distance between the center of the fan and the center of each loudspeaker being 6 cm. The signals from the condenser microphones used as error sensors were employed in a multi-channel filtered-x LMS algorithm, which generated the control signals. To monitor the global effect of various control configurations, a 5 ft. radius semicircular boom, to which thirteen ½" condenser microphones were attached at equal angle increments, was rotated in fifteen degree increments in order to obtain a complete hemispherical measurement. The global mean-squared pressure reduction for each harmonic of the BPF was then calculated and the fan's directivity with and without ANC was plotted. All measurements were made in an anechoic chamber with working dimensions of 7.9 x 4.6 x 4.6 m.

4. Tests Performed and Results

The first test performed was a three-dimensional measurement of the fan's directivity for each of the four harmonics of BPF, shown in Figure 2. The color map and radius of the surface provide redundant information on the fan's directivity. The mesh overlay can be used to visualize the degree of omnidirectionality of the radiation, though the radiation is somewhat skewed towards the on-axis direction because of the offset of the fan due to the height of the enclosure. As expected, the directionality and spatial complexity of the radiation increases with frequency. The substantial notch in the fundamental tone's directivity along the negative Y axis is caused by diffraction effects due to the dimensions of the enclosure.

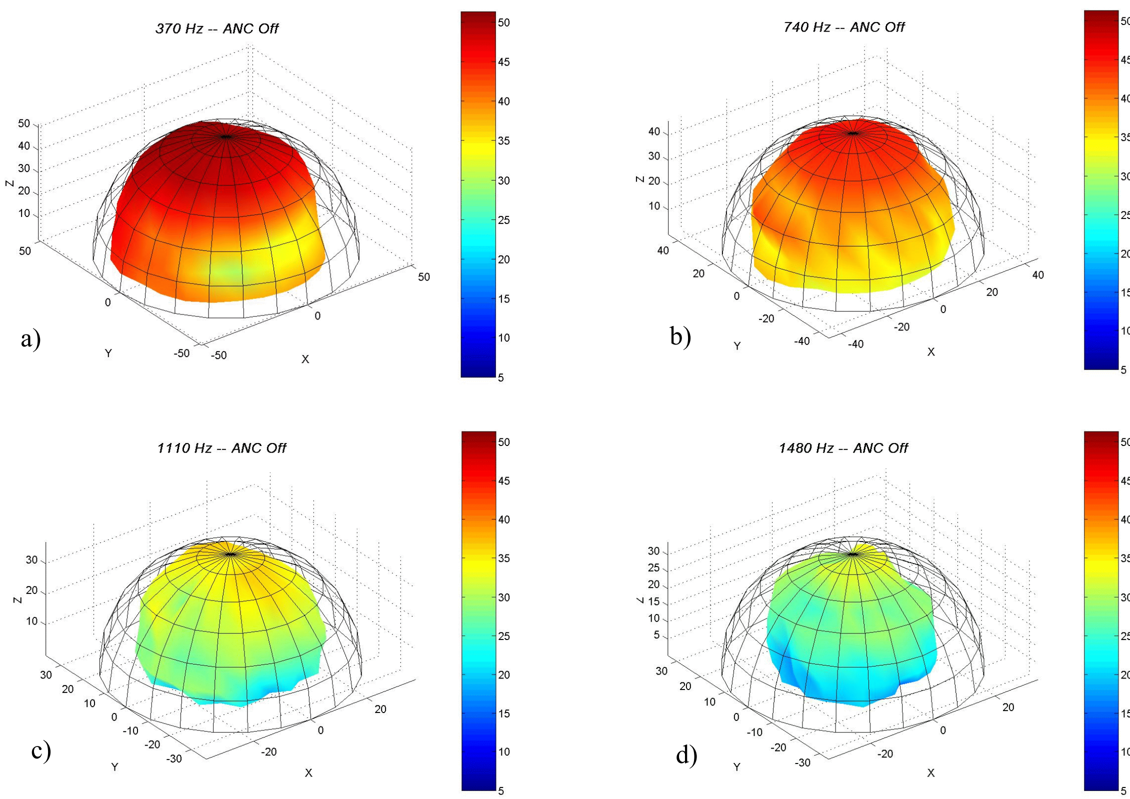

Figure 2. Directivity of BPF and harmonics for fan with obstruction, mounted in enclosure. Color values and radius indicate calibrated sound pressure level in dB.

The results from a two channel test, with the two error microphones located along the theoretical nulls, are shown in Figure 3, with the mesh overlay representing the directivity of the fan without control. The global mean-squared pressure reductions measured with the boom microphones for the first four harmonics of the BPF were 7, 14, 6, and 5 dB respectively. Figure 3a shows that with the ANC system engaged, the notch in the directivity of the fundamental disappears, causing the radiation to actually increase in that direction. The lesser attenuation of the BPF than that of the second harmonic (shown in Figure 3b), consistent with virtually all multi-channel tests, may be attributed to the frequency response of the loudspeakers, which begins to roll off below about 600 Hz. The reduction for the third and fourth harmonics, shown in Figures

3c and 3d, is markedly more in some areas than in others, and exhibited a certain inconsistency from test to test, even with the microphones located along the calculated ideal directions.

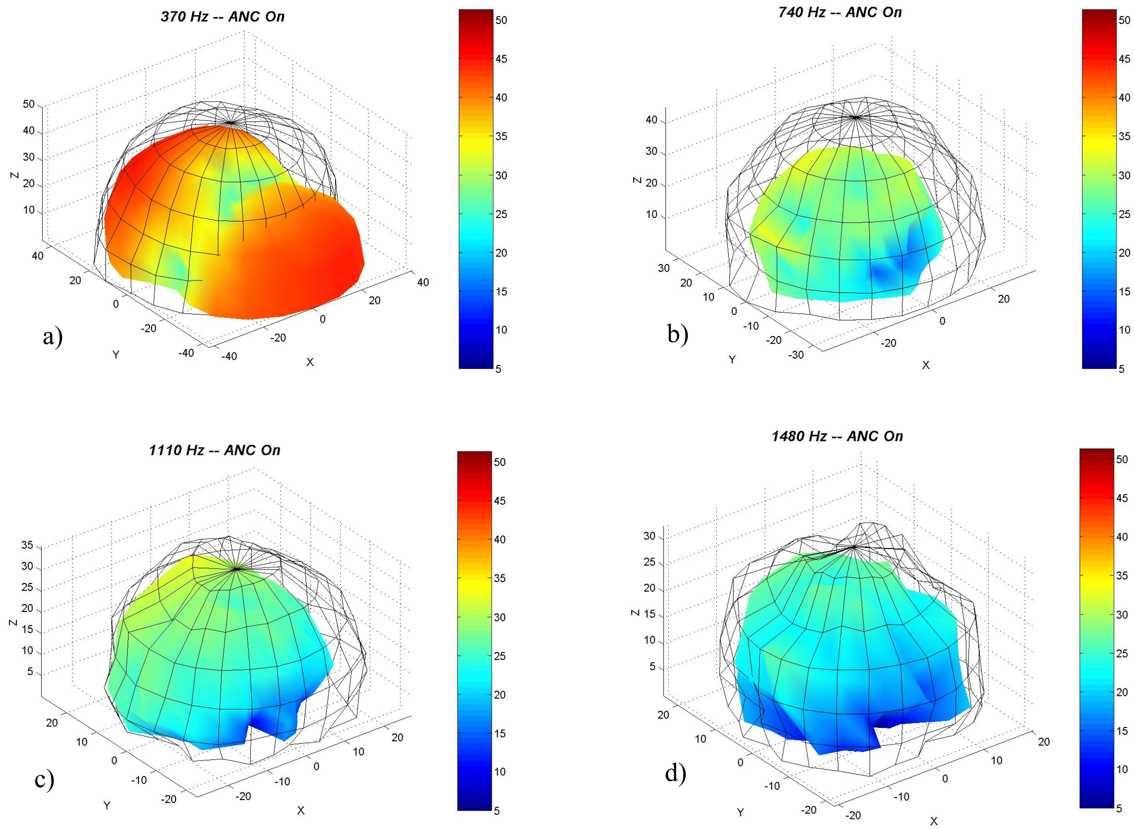

Figure 3. Directivity of BPF and harmonics with (surface) and without (mesh) two channel ANC. Color values and radius indicate calibrated sound pressure level in dB.

Because of the closed near-field null created by minimizing the power of four control sources (seen in Figure1b), the four channel configuration with the four error microphones located along that ring received significant attention. Displayed in Figure 4 are the global mean-squared pressure results from one test performed with the error microphones located symmetrically between loudspeakers. In this case, the reductions for the four harmonics of the BPF were 9, 19, 16, and 14 dB. Again, there is a slight increase in radiation in the notch region of the fundamental, but the overall reduction is more uniform. The reduction on the subsequent harmonics, though, has increased dramatically from the two channel test. In fact, the reduction of the third and fourth harmonics, shown in Figures 4c and 4d, represents a virtually global attenuation down to broadband levels.

5. Conclusion

Multi-channel active control of tonal noise from axial cooling fans has been successfully demonstrated, showing a marked improvement over previous single channel efforts. The point source analysis and experimental verification demonstrate that for this application, there are extreme near-field error microphone locations that consistently lead to significant global reductions in the mean-squared pressure for the first four harmonics of the BPF. It is anticipated that if loudspeakers with a better response at low frequencies were used, the reductions for the BPF could be greatly improved, matching or exceeding those achieved for the higher harmonics.

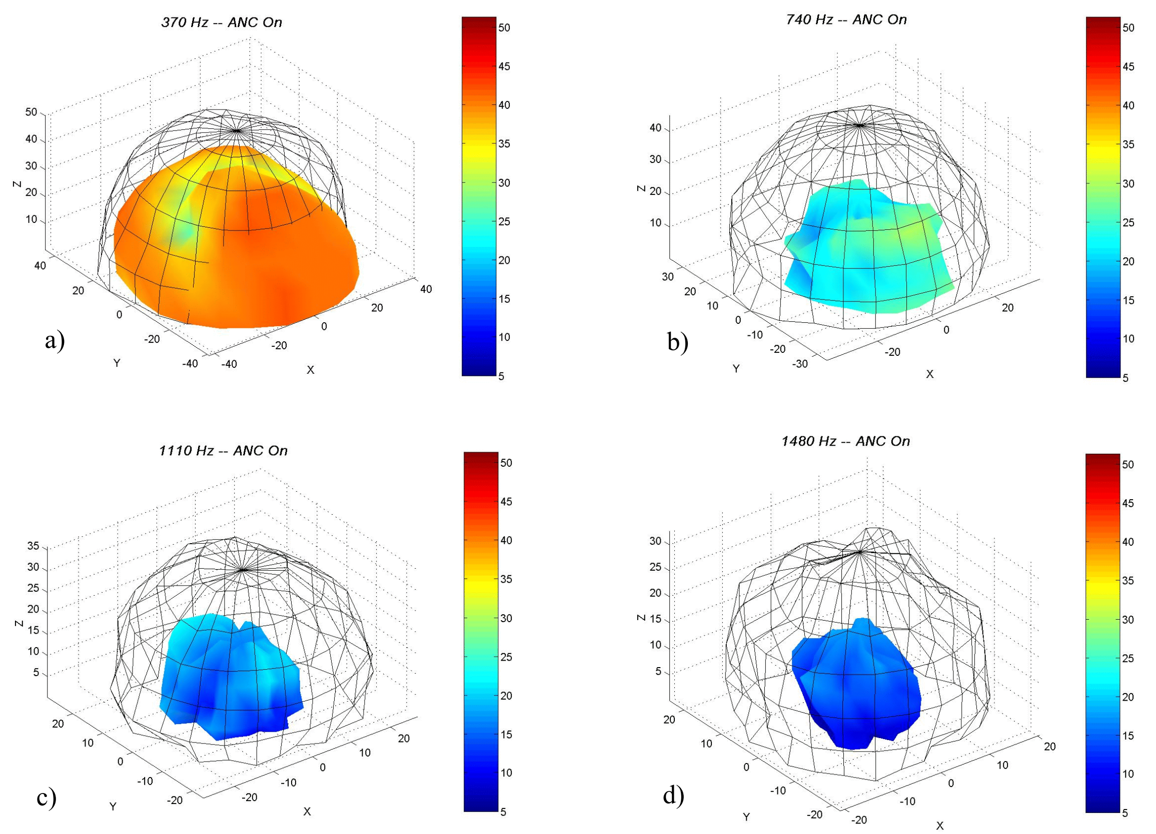

Figure 4. Directivity of BPF and harmonics with (surface) and without (mesh) four channel ANC. Color values and radius indicate calibrated sound pressure level in dB.

Finally, the four channel system, with the speakers and microphones contained in a single array surrounding the fan, represents a practical control configuration, thus constituting a significant step toward an employable active control technology.

References

1. W. S. Chiu, G. C. Lauchle, and D. E. Thompson, "Subsonic axial flow fan noise and unsteady rotor force," *J. Acoust. Soc. Am.* **85**, 641-647, 1989.
2. D. A. Quinlan, "Application of active control to axial flow fans," *Noise Control Eng. J.* **39**, 95-101, 1992.
3. M. Q. Wu, "Active cancellation of small cooling fan noise from office equipment," *Proc. Inter-Noise 95*, Newport Beach, CA (Noise Control Foundation, Poughkeepsie, NY, 1994), pp.71-76.
4. G. C. Lauchle, J. R. MacGillivray, and D. C. Swanson, "Active control of axial-flow fan noise," *J. Acoust. Soc. Am.* **101**, 341-349, 1997.
5. P.A. Nelson and S. J. Elliott, *Active Control of Sound* (Academic Press, London, 1992), pp. 231-271.