25 YEARS AGO, ACTIVE CONTROL FIRST APPEARED AS A GREAT SOLUTION FOR FAN NOISE. WHAT HAS HAPPENED?

Steve WISE

WISE ASSOCIATES, 1409 East Skyline Drive Madison, WI 53705 USA

SUMMARY

Active noise control (ANC) will eventually be as ubiquitous for fan applications as we now see with electronic variable frequency drive control (VFD). Not unlike VFD, early ANC was complicated, expensive, problematic in its application, and of questionable reliability. Just as it took VFD suppliers decades to refine the product, ANC researchers are slowly solving the puzzle of application know-how and hardware and software refinement.

INTRODUCTION

The author first installed an active fan exhaust silencer at an industrial plant in 1987. There are now 11 units at the site, still operating, thus answering one of the fundamental questions at the time – that they are reliable. The superior low-frequency noise reduction, especially dramatic on tonal spectra, was clearly demonstrated. Compared against the alternative traditional passive silencers, the 1" (250 Pa) pressure loss savings leads to reduced fan power consumption that has recovered the original installation cost many times over.[1]

In addition to reliability concerns, there are other factors that suppressed wide application over the ensuing years; 1) the cost was high and the energy benefits not well appreciated; 2) initially, limited application know-how; 3) less stringent guidelines for acceptable noise levels – specifically a disregard for the annoyance of low-frequency noise and especially pure tones; and 4) now-expired fundamental patents in the hands of a few small companies who failed to sustain long enough for market success.

Along with the present low cost of the electronics, evolving market factors have increased the value of the benefits such that it is time for a fresh look at widespread use of this technology, especially in HVAC applications.

This paper highlights some of the 1000 installed units with which the author has direct familiarity, both industrial and HVAC, answering questions about performance predictability along with lessons learned.[2] The systems over the years have provided exceptional low-frequency noise reduction while cumulatively saving approximately 30 million kW-hrs power consumption, with respective reduction of 20-35,000 tons of CO_2. Low-noise, high efficiency fan installations are an attainable goal for the future.

INDUSTRIAL APPLICATIONS

The first installation, dating to 1987, was performed on a collection of induced-draft fans located on the roof of a plastic resin manufacturing plant in Wisconsin, USA.

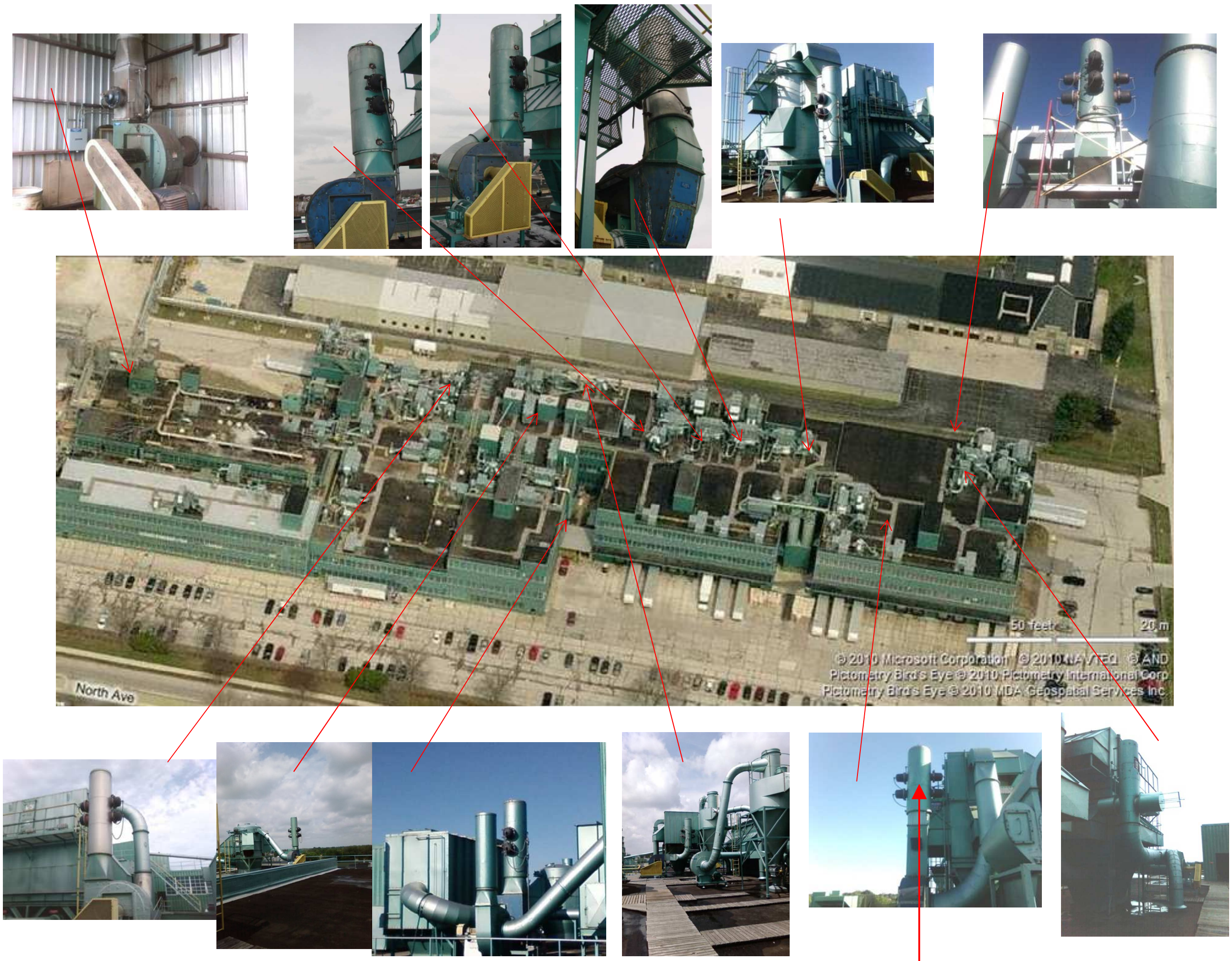

Figure 1 –Multiple ANC systems on plant roof

In each case for Figure 1 above, the speakers and microphones were mounted on existing discharge stacks. Cables from those components are run in conduit to controllers located indoors nearby. Mechanical and electrical work amounted to approximately one day of labor for each unit; however, unlike the weight burden of passive silencers, no heavy-lift equipment, nor stack supports, were required. Thus the installed cost is favorable compared to the alternatives.

The speakers are located on the side wall of the stacks so as to not restrict the airflow, allowing the fans to operate at the same rpm, airflow and static pressure load as originally designed.

The fans draw air from inside the plant through fabric filters. As such, the temperature is moderate at approximately 80F (27C), and the exhaust flow is clean, meaning that the speakers and microphones are in a benign environment. Typical operation at the plant is daytime only, whereupon the speakers and microphones cool to winter temperatures below freezing at night, but have no problem with proper function the following mornings.

Some speaker replacement has been required. Typically, with speaker output necessitating no more than ¼ of x_{max} excursion, lifetimes can exceed 15 years in clean environments. In applications where speaker excursions approach x_{max}, shorter lifetimes have resulted. It should be noted that the fabric filters typically require bag replacement at least yearly, so the cost and timing of occasional speaker replacement is a negligible fraction of the operating expense for the fan system in general.

Generally, there is redundancy in speaker selection such that ANC function can be achieved even with one or more speakers in need of replacement.

Acoustical Performance

Commonly used backward-curved centrifugal fans mostly have problem noise at the blade-pass frequency. These low-frequency tones are dramatically eliminated by the ANC system. Owing to various combinations of number of blades and fan speeds for the assorted equipment at the Figure 1 reference location, the resulting composite noise spectrum measured at a central roof location, seen in Figure 2, shows a series of pure tones dominating a lower broadband level. Individual tones are reduced by up to 30 dB or more on a narrowband basis, and up to 20 dB in an octave band analysis.

It is significant to note that overall dBA reductions can be modest, usually less than 10 dB, in part because the reduction occurs at de-weighted low frequencies. But a change as small as 3 dBA can still have dramatic subjective impact; and in fact, many ordinances have 5-10 dB penalties for tonal spectra, so elimination of the problem tones can have a bonus even in objective on/off evaluations.

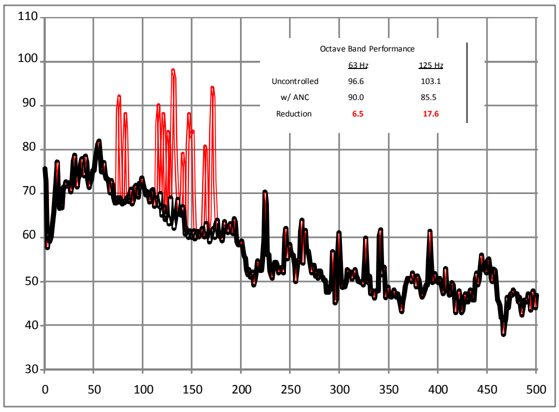

Figure 2: Combined Fan Exhaust Noise Spectra With and Without ANC.

A fundamental ANC characteristic is that a single channel of control can only respond to plane waves of sound propagation in the duct. The upper frequency for plane waves relates to duct diameter by:

For speed of sound, c, in feet/sec and d in inches

$$f = 7 * c / d$$

For c in m/s and d in meters

$$f = 0.58 * c / d \qquad (1)$$

When the frequency of concern exceeds the upper limit for a given stack diameter, that indicates the possibility of higher-order modes where multiple channels of control are required. A speaker is required in each modal zone, and in fact, since the orientation of the zone can be variable in a round duct, a minimum of n+1 phase-linked speakers is required for n modal zones. It is generally not practical to apply ANC to large round ducts (or small ducts with high frequency noise). Thus, the use of multiple speakers around the circumference, as in the Figure 3 examples, is necessary just to provide enough speaker output capacity to match the sound power level of the fan.

Figure 3-Various industrial fan ANC installations.

From left to right in Figure 3 are ANC installations: atop a separator on a gas processing plant; on the discharge stack for vacuum pump at a paper mill; and on the duct between fan and mechanical dust collector for a paper scrap processor.

On the vacuum pump application, the airflow is saturated with moisture, requiring protection of the speakers, typically with rubber membranes. These repel water droplets but can allow vapor migration – to prevent this and the potentially damaging condensation on the speaker electrical elements, the cans are pressurize to maintain a constant supply of clean air inside the enclosure.

For the paper scrap collector, fine-mesh screens block the buildup of material on the speakers. Again, with the flush mounting of speakers on the duct circumference, there is no impedance to the flow of material in the duct.

Note that when the speakers inject the cancelling sound waves into the duct, these propagate both upstream and downstream. Downstream, the net result of the "opposite phase" is reduced sound pressure. Upstream, the cancelling sound can propagate to the fan and then be reflected back toward the speakers. Under the right conditions of speaker location, speed of sound, and wavelength, this can produce an impedance mismatch whereupon the speaker output is negated. If the conditions are fixed, a safe speaker location can be chosen. But if the frequency changes, or if the speed of sound changes due to temperature fluctuations prevent a fixed solution, the problem can be resolved by using directional loudspeakers that allow only downstream propagation of the cancelling sound waves. Use of this technique is indicated in the above examples where speakers are positioned in successive planes along the duct path. Examples in Figure 4 show another way to avoid the problem, by having the speakers immediately at the fan discharge.

Figure 4 – ANC speakers located adjacent to fan discharge

HVAC APPLICATIONS

Cool, clean operating conditions prevail for the application of ANC to fans used in heating, ventilating and air-conditioning (HVAC) equipment. Combined with the relatively modest sound power levels, the speaker requirements are accommodated at low cost. Figure 5 shows some examples of how the components are easily included in typical duct runs from centrally located air handlers.

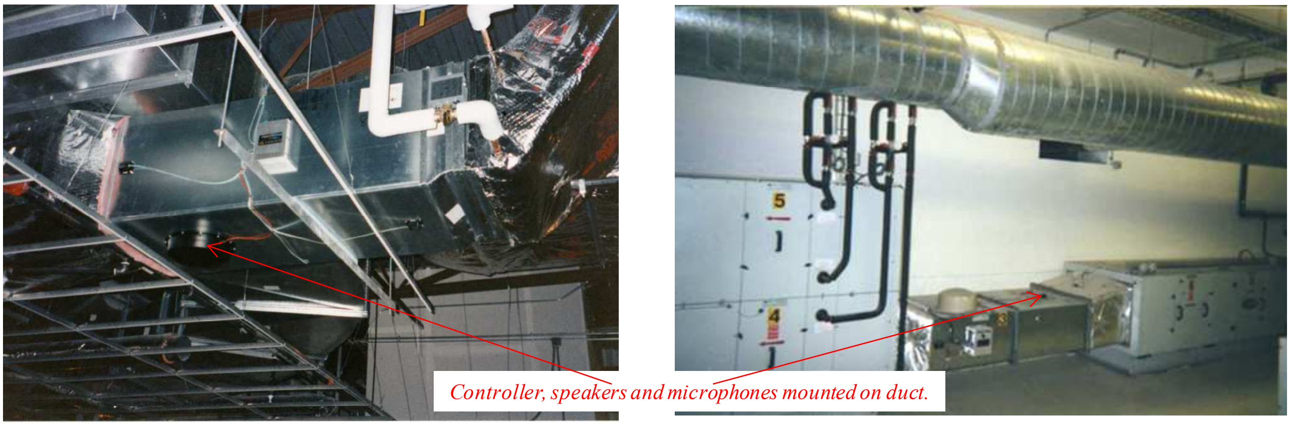

Figure 5- HVAC installations

There often is a dominant blade pass frequency tone in HVAC fan noise spectra. But almost always there are significant broadband components as well. The ANC on/off spectra plotted in Figure 6 shows dramatic reduction for both, as measured at the in-duct control microphone.

The noise level after ANC (black curve) in part consists of actual residual propagating fan noise, but most of it is in fact "pseudo-noise" from localized turbulence pressure fluctuations exciting the microphone. Regardless of the level of noise entering the ANC system, this represents the coherent signal floor limit of cancellation. Lower duct velocities result in smaller scale turbulence, which in turn lowers the pseudo-noise floor and improves the actual fan noise signal detection at the microphone and results in greater cancellation. Conversely, faster air flow will raise the residual signal level across all frequencies, thus limiting performance.

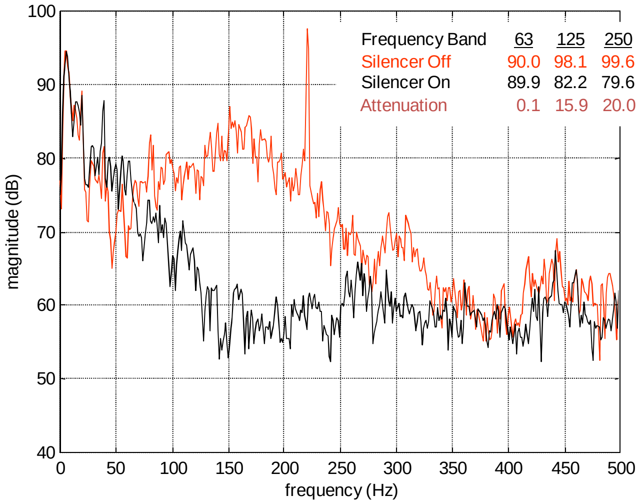

Figure 6 - ANC on/off narrowband fan noise specta

20 dB of reduction in any octave band is superlative. In general, even when the ductborne noise has this amount of ANC reduction, there are flanking noise paths such as via mechanical room walls that limit the total effect in the noise-sensitive space.

Hybrid Active-Passive Systems

The prior examples in this paper all use circumferentially mounted loudspeakers. The advantage is zero flow restriction, but ANC with outboard speakers only works up to the frequency limits of plane waves, or the first few higher modes in the cases of multi-channel control. In very large ducts with many higher-order modes, or, if there is a need for attenuation across all octave bands, subdivision of the cross-section with multiple ANC systems mounted in interior sound absorbent baffles offers a complete solution.[3] Figure 7 shows two examples. On the left is fabrication-stage insertion of the baffles. The picture to the right is a more complete assembly, with end-caps, but still indicating accessibility to the speakers and microphones should any service be required.

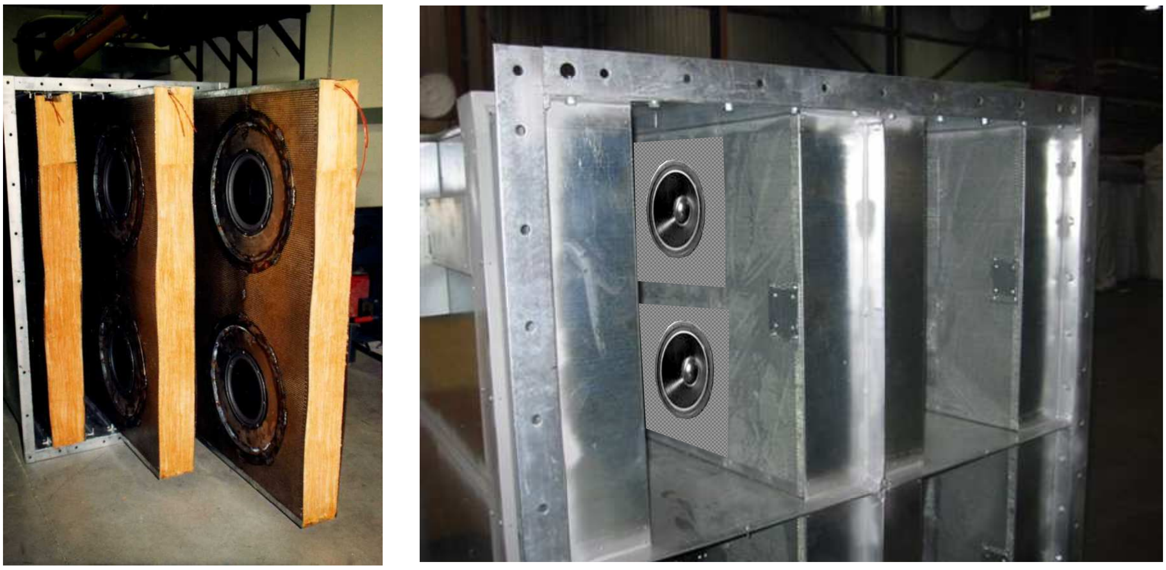

Figure 7 – Hybrid active-passive silencers

In the above cases with 6-12 inch (150-300 mm) thick baffles, one might think that the passive sound absorption alone would be sufficient. But in applications with low-frequency noise sensitivity, there can be an excess of residual low-frequency noise. Figure 8 shows performance as applied to a large axial fan.

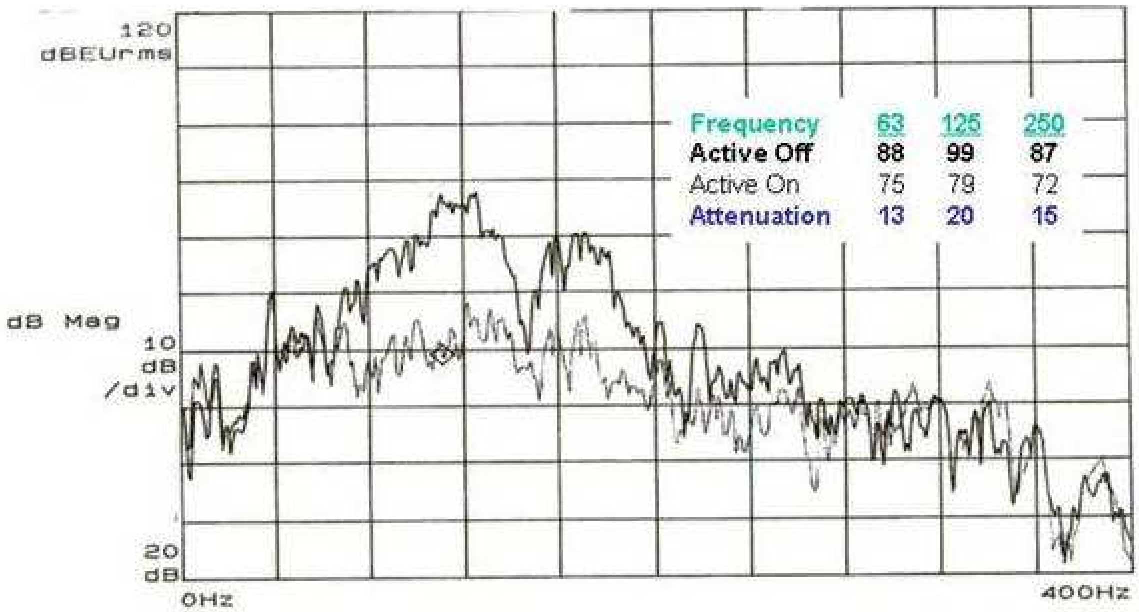

Figure 8 – Hybrid silencer, multi-module ANC performance on a large axial fan

PERFORMANCE PREDICTABILITY

As mentioned above, the level of residual noise after cancellation is primarily limited by airflow turbulence which varies with duct velocity. Thus, as fans get louder, ANC performance increases, driving residual noise down to the limit of a given airflow. Bear in mind that laboratory testing of fan noise has tolerances ranging up to ± 6 dB at the lowest frequencies. Correspondingly, installation of fans carries at least as much uncertainty with regard to the actual level of fan noise that will result from field conditions. With ANC, the result is reliably assured, as opposed to passive attenuation that has fixed attenuation.

Proof of this concept is summarized in Table 1, which shows tolerances of residual noise after application of ANC, measured in 3 site locations with multiple, identical, fan/duct layouts.

Table 1 - Variation of fan sound power level with and without ANC

Installation	Fan Noise Variation	Cancellation	Residual Noise Level
	before ANC	Variation	after ANC
24 AHUs at 20,000 cfm (9.4 m^3/s), 3" (750 Pa) static pressure	+ 6 dB /- 7 dB	5-15 dB	± 2 dB
26 Fan Inlets at 75000 cfm (35 m^3/s), 5" (1250 Pa) static pressure	± 5 dB	6-14 dB	± 3 dB
18 Fan Box units at 1,200 cfm (0.5 m^3/s), 0.5" (125 Pa) static pressure	+ 10 dB /- 2 dB	2-10 dB	± 2 dB

The differences in uncancelled fan noise might be attributed to manufacturing variances in the fan wheel and scroll, wheel-to-scroll cutoff clearance variance, dynamic balancing, belt tension, etc., which are not unusual. There is also some variation in discharge duct stiffness and vibration since the support hangers are field-installed and each location is unique.

This is a problem for design engineers when using passive silencers. They might be undersized, or, if selected based on the worst case can have excessive pressure loss, increasing the fan load, thus further increasing the noise in a “ratchet” effect. The fact that the result after ANC is consistent is a valuable aid to design engineers.

SAVINGS IN FAN POWER CONSUMPTION

Minimizing pressure loss by use of ANC allows for smaller fan/motor capacities, which factors into cost savings for the installation. But beyond first costs, even more significant is the power savings resulting from the lower fan load.

Of course, the ANC system requires some power to function. Speakers must generate sound power equivalent to the level of fan noise to be cancelled. But, for reference, with 120 dB at only 1 watt of energy, and speaker efficiencies ranging from 1-10% typically depending on installation specifics, the range of controller power consumption for examples shown in this paper range from 25 to 300 watts, compared to ~ 1 to 30 kW additional for each fan if a passive silencer was used.

Table 2 below shows potential energy savings and greenhouse gas reductions from various assortments of fan sizes, pressure loss reduction (ANC vs. passive control), and power cost. The first 3 lines are from 3 actual sites, followed by possible scenarios for a single unit. The last line represents a composite total of all the installations with which the author is familiar.

Table 2: Energy savings and CO^2 reductions for ANC applications

Average Airflow		# systems	years	Pressure loss		% eff.	Hours	Power (Mw-hr)	Cost / kw-hr	Savings (USD)	tons CO_2 (typ)
cubic ft/min	m^3/s			in. w.g.	Pa						
16000	7.54	11	20	1	250	75	4380	2,414	0.07	$ 168,993	1,576
70000	32.98	26	15	0.7	175	75	8760	26,213	0.08	$ 2,097,050	17,117
1500	0.71	18	15	0.2	50	75	4380	56	0.03	$ 1,667	36
10000	4.71	1	1	0.2	50	75	8760	3	0.03	$ 82	2
10000	4.71	1	1	0.7	175	75	4380	5	0.42	$ 2,016	3
10000	4.71	1	1	0.3	75	75	8760	4	0.42	$ 1,728	3
10000	4.71	1	1	0.7	175	75	4380	5	0.2	$ 960	3
10000	4.71	1	1	1	250	75	8760	14	0.3	$ 4,115	9
8000	3.77	1000	20	0.5	125	75	6000	75,161	0.42	$ 31,567,821	49,080

DURABILITY

System reliability has been proven over the years. Component life, and failure examples are:

- Microphones; 200 years predicted for clean, cool environments. No failures to date.

- Speakers: Up to 20 years (some original units have never been replaced). Ductborne contaminants have affected life at ~25 % of industrial sites. High excursions have produced routine surround failures at ~30% if industrial sites, at about 5 years on average. No HVAC installation speaker has ever been replaced.

- Controller: Perhaps up to 20 years. Less than 5% have required service. Of those, about half have been due to incidental damage (such as from dusty environment or accidental water intrusion). Others have seen primarily capacitor burnout.

THE FUTURE

If there is a need for reduced low-frequency noise, and if energy efficiency of fan installations is given full evaluation, then active noise control represents an affordable technique for high performance. The main task that faces us is creative integration into fan systems.

BIBLIOGRAPHY

[1] S. Wise, G. Leventhall – *Active noise control as a solution to low frequency noise problems*. 12th Int'l Meeting on Low Frequency Noise and Vibration and its Control, Bristol UK, **2006**

[2] S. Wise, J.-F. Nouvel, V. Delemotte – *The first 1000 active duct silencers installed in HVAC systems – a summary of applications, successes, and lessons learned.* Internoise 2000, Nice, **2000**

[3] T. Paige – *Combination Sound and Vibration Isolation Curb for Rooftop Air-Handling Systems,* NOISE-CON, Minneapolis, Minnesota, **2005**

stevewise@att.net