# Measurement and Evaluation of Blade Passage Frequency Fluctuations

Physics 492R Capstone Project Report

Cole V. Duke

Scott D. Sommerfeldt (Advisor)

Kent L. Gee (Advisor)

Connor R. Duke (Collaborator)

Presented at Noise-Con

Reno, NV

October 23, 2007

Reno, Nevada

NOISE-CON 2007

2007 October 22-24

# Measurement and evaluation of blade passage frequency fluctuations

Cole V. Duke[a]

Scott D. Sommerfeldt[b]

Kent L. Gee[c]

Connor R. Duke[d]

Brigham Young University

N-281A ESC

Provo, UT 84602

## ABSTRACT

In the active control of tonal noise from cooling fans, one factor that can limit the achievable attenuation is fluctuation of the blade passage frequency in time. Large fluctuations in a short time can hinder the algorithm from converging to the optimal solution. Some fans have steadier speeds than others, which can be due to unsteady driving mechanisms or the physical structure of the fan. Environmental effects such as back pressure and unsteady blade loading can also cause the fan speed to fluctuate. The shifting in the blade passage frequency will be measured using a

[a] Email address: coleduke@gmail.com
[b] Email address: scott_sommerfeldt@byu.edu
[c] Email address: kentgee@byu.edu
[d] Email address: connorduke@gmail.com

zero-crossing technique to track the frequency of each cycle. Blade passage frequency fluctuations will be presented for various driving mechanisms and environmental conditions. Techniques to minimize frequency shifting will also be discussed.

## 1. INTRODUCTION

As computer processors continue to get faster, the need for effective cooling in computers grows. Axial cooling fans are the most typical type of computer cooling. As computers get faster, the fans must move more air to cool the computer to a reasonable temperature, and as fans move more air, they typically create more noise. This can be a big problem in many settings, including offices and computer labs in general. Controlling this noise through active noise control techniques is the ultimate motivation of this research.

Previous work has been done with active control of computer fan noise, and implementation of a filtered-x algorithm has been shown to control the tonal noise from axial cooling fans.[1-3] A feed-forward technique was used in which a reference signal was obtained from the fan, and microphones were used as error sensors for the algorithm to continually correct itself. This system minimized the sound pressure of the correlated frequency content between the reference and error signals.

One factor that can limit the achievable attenuation of the tonal fan noise is fluctuation of the blade passage frequency (BPF) in time. The achievable attenuation of the tonal fan noise is limited by the coherence between the error sensors and the reference signal. If there is any kind of delay between the reference signal and the error signal, it can reduce the achievable attenuation, particularly if the BPF is changing in time. If the BPF fluctuates in time, it is also more difficult for the algorithm to converge and control the noise, no matter how well the error and reference signals are correlated. A convergence parameter that controls how quickly the algorithm tracks the fan noise can be changed, but if the system converges too quickly, it has a higher probability of becoming unstable.[4-5] The convergence parameter controls how the control filter changes after each iteration of the algorithm, and it dictates how quickly the algorithm can converge on a global minimum of sound pressure. If the convergence parameter is too small, then it will not track changes in the BPF, but if it tracks too quickly, it can overshoot the minimum sound pressure, and continue until the system becomes unstable. For this reason, it is important to know how quickly the BPF is changing. It is equally important to know if the tachometer and the error sensors track BPF fluctuations quickly and accurately.

Multiple factors can cause the BPF to fluctuate. The factors explored in this paper are the speed of the fan, the pressure drop across the fan, and the overall construction of the fan. It is possible that the driving mechanism can be more unstable when the fan spins faster, and this is why the speed of the fan is thought to affect the steadiness of the BPF. In many fans, the driving mechanism is a pulse-width-modulation (PWM) signal, which uses a steady DC voltage modulated with a high-frequency signal. The duty cycle of the signal can be changed to change the effective voltage that the fan receives, but it can possibly be less stable than a fan driven with a simple DC voltage, and this will also be explored.

In most cases, an internal tachometer signal from the fan was used as the reference signal for the active noise control system. When a tachometer signal was not available, an emitter-detector pair was used to create a pulse at each blade pass.[6] The reliability of the internal tachometer was also studied to determine whether or not it was a reliable reference signal.

## 2. PROCEDURES

### A. Measurement

All fans were tested in an anechoic chamber mounted on an ISO 10302 fan testing plenum. The plenum was used to control the pressure drop without changing the acoustic field.[7] Two ½-inch

Type I ICP microphones were placed in the near-field of the fan, and one was placed in the far-field. A strip of reflective tape was placed on the inlet hub of each fan, and a photo tachometer was used to track the actual rotational speed of each fan. Of the seven fans tested, only five had built-in tachometers, and these were recorded. All signals were recorded using a 200 kHz sampling rate. For fans driven with a constant DC voltage, three different voltages were supplied (6V, 12V, 15V) to drive the fans at three different speeds. For the fans driven with a pulse-width modulation (PWM) signal, a square wave at 25 kHz with three different duty cycles (60%, 70%, 80%) was used to obtain three different speeds. Measurements were recorded for three different pressure drops at all of the three speeds for each of the fans. All fans studied were 60mm in diameter.

### B. Zero-Crossing Technique

For the purposes of this study, it was necessary to have enough time and frequency resolution to be able to observe small changes in frequency over a short period of time. To perform the analysis in the frequency domain, it is not possible to have sufficient resolution in both frequency and time. For a given number of sample points (N) and sample frequency (Fs), the frequency and time resolution are defined as

$$T = \frac{N}{Fs} \tag{1}$$

$$\Delta f = \frac{Fs}{N} \tag{2}$$

$$\Delta f = \frac{1}{T} \tag{3}$$

As can be seen in Equation 3, frequency resolution cannot be increased without decreasing the time resolution, and vice-versa. To overcome this limitation, a zero crossing technique was used in the time domain. The significant broadband noise associated with fan noise, as well as harmonics of the BPF, made it necessary to band-pass filter in the frequency domain to obtain valid results using the zero-crossing technique. The filter cutoff had to be very steep to attenuate all noise outside the desired frequency range. To achieve this, all information outside of a specified frequency range was simply set to zero. This is the equivalent of a flat-top window in the frequency domain, or a digital brick-wall filter with infinite steepness and no ripple in the pass band.[8-9] This steep filter cutoff creates amplitude artifacts in the time signal, but does not affect the zero-crossings of the signal.

After filtering, an inverse Fast-Fourier-Transform (FFT) was performed, and the entire time signal was analyzed. Each zero crossing was evaluated, and the period was then calculated for each oscillation in the time signal.[10-11] Linear interpolation was used to obtain more precise zero-crossing times. All blade passage frequencies were below 1000 Hz, and a 200,000 Hz sample rate was used. Because of this, at least 200 data points were obtained for every cycle in the time domain.

### C. Evaluation

The zero-crossing technique described above creates an array of frequencies over time. Any variations in this signal signify a change in fan speed. Fluctuations in the BPF are observed by simply looking at the graph of frequency over time, but two additional methods were also used to quantify the BPF fluctuations.

The first method used an FFT to evaluate the magnitude and frequency of the BPF fluctuations. First, using the zero-crossing technique discussed above, an array was built with the frequency of every cycle of the time signal. An FFT was then performed on the frequency array to evaluate the frequency and magnitude of BPF fluctuations. In an ideal situation where the frequency was constant over time, the spectrum would be a delta function at 0 Hz. Faster changes in frequency are then shown as higher frequency content.

$$s = \left( \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2 \right)^{\frac{1}{2}} \tag{4}$$

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \tag{5}$$

The second method used the standard deviation as defined in Equation 4. When taking the standard deviation of the entire signal, most of the useful information was lost because there were so many points with relatively small fluctuations. For this reason, the standard deviation was evaluated for consecutive small blocks of points, which were graphed to show variation in the BPF.

## 3. RESULTS

### A. Effects of Speed, Pressure, and Other Parameters

The parameters investigated in this study include the speed of the fan and the pressure drop across the fan, as well as the physical characteristics of the fan. While some fans showed key differences in response to changing these parameters, most did not. This study was not intended to be a comprehensive analysis of all possible causes for fluctuations in the BPF. Instead, only a comparison of specific parameters was considered.

Figures 1 and 2 show how increased overall speed can affect the fluctuations of the BPF with the other two parameters held constant. Both figures display measurements from the same fan with the same pressure drop across the fan. This particular fan was driven with a PWM signal. The black line shows the results for the photo tachometer, and the red line shows the results for the near-field microphone. As can be seen by the y-axis on the plots on the left, the high speed case is only an increase of approximately 25% in BPF, but it is apparent that this increase has a large effect on how the BPF fluctuates. It can be seen that there are sharp changes in the BPF over time, which will be especially detrimental to the active control system. By comparing the two left plots, it is clear that the BPF is fluctuating much more in the high-speed case. These differences are also apparent in the other two plots. These fluctuations in the high-speed case can been seen in the middle plot as high-frequency information. The changes can also be seen in the right-most plot as standard deviation greater than zero.

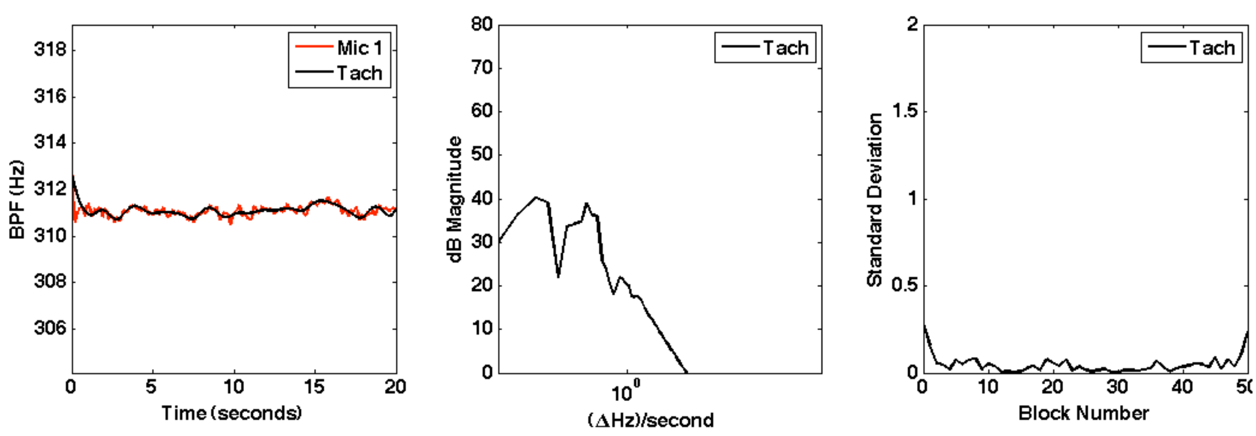


**Figure 1:** Low speed case: Fan #1, 24.9 Pa pressure drop, 60% duty cycle PWM signal

BPF vs. time (left), FFT of BPF vs. time (middle), Standard deviation of BPF vs. time (right)

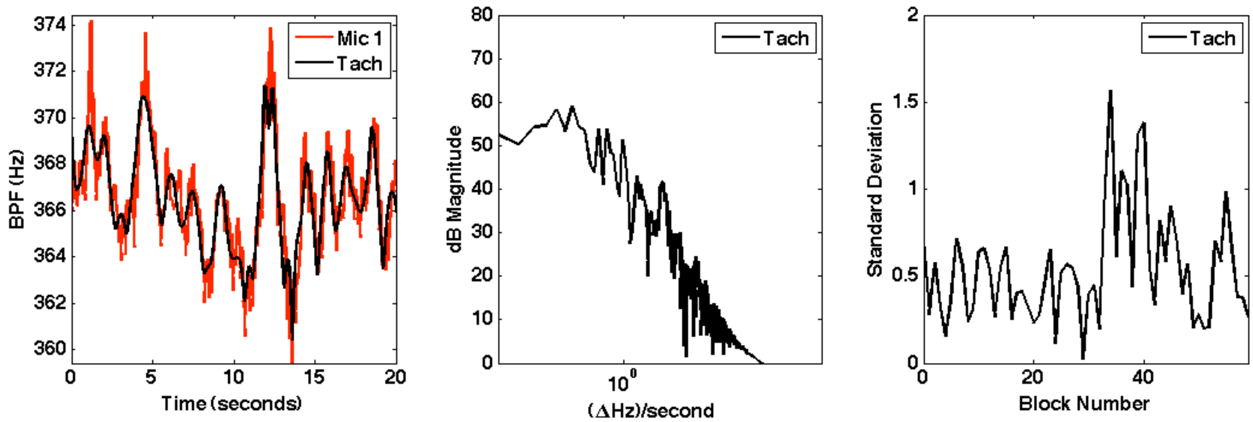


**Figure 2:** High speed case: Fan #1, 24.9 Pa pressure drop, 80% duty cycle PWM signal

BPF vs. time (left), FFT of BPF vs. time (middle), Standard deviation of BPF vs. time (right)

In Figures 1-6, the left plot shows the BPF as it changes over time, the middle plot shows the FFT of that signal, and the right plot shows the progressive standard deviation discussed above. All plots are shown with the same scales to make comparisons easier between the different cases.

Figures 3 and 4 show how a variation in pressure drop across the fan can affect the BPF fluctuations. This particular fan was driven with a constant 15V in both cases. Figure 3 shows the low-pressure case and Figure 4 shows the high-pressure case. As can be seen in Figure 4, a higher pressure drop across the fan can cause the BPF to fluctuate more, but the changes are more gradual than the case above. This can be observed by the fact that the FFT and standard deviation plots are fairly similar to each other in figures 3 and 4. It is apparent that the BPF is fluctuating more in the high-pressure case, but the fluctuation are more gradual than I the fluctuations shown in figure 2. This type of BPF fluctuation is important to understand, but will be less detrimental to the noise control algorithm.

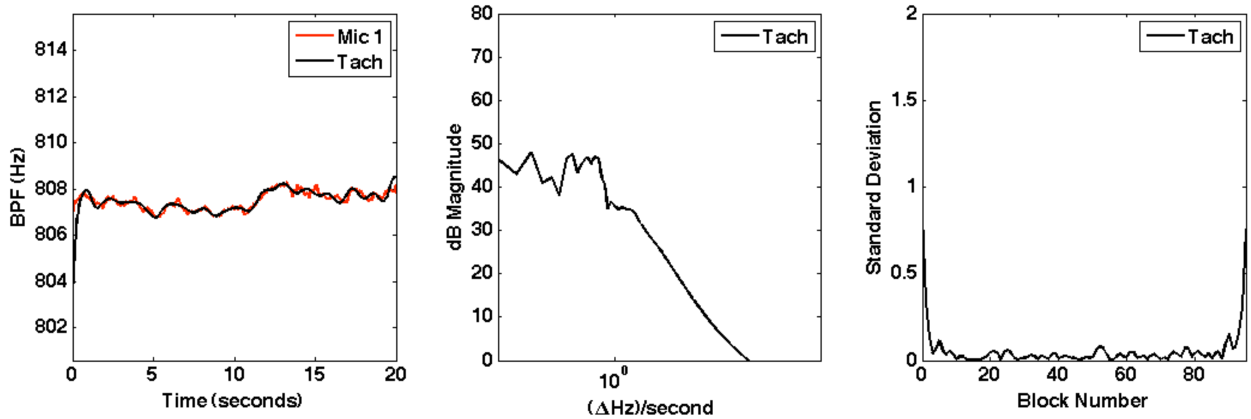


**Figure 3:** Low pressure case: Fan #2, 0 Pa pressure drop, 15V constant driving voltage

BPF vs. time (left), FFT of BPF vs. time (middle), Standard deviation of BPF vs. time (right)

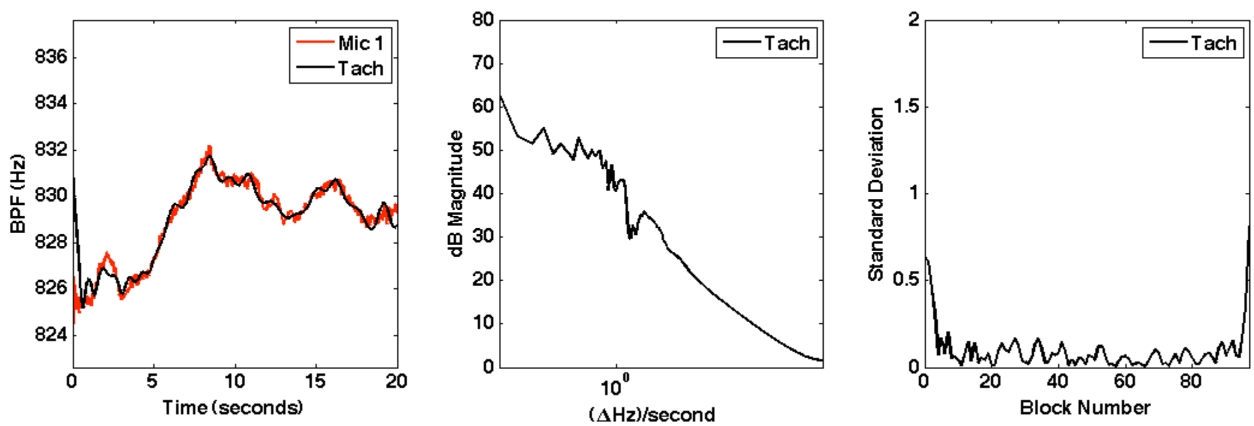


**Figure 4:** High pressure case: Fan #2, 24.9 Pa pressure drop, 15V constant driving voltage

BPF vs. time (left), FFT of BPF vs. time (middle), Standard deviation of BPF vs. time (right)

While the differences are apparent in each of the cases above, some fans showed little or no difference in BPF fluctuations with variations in pressure and speed. Figures 5 and 6 show one fan in particular. As the first fan discussed, this fan was also driven using a PWM signal. Figure 5 shows the results for low speed and low pressure, and Figure 6 shows the results for high speed and high pressure. These are the two cases that might create the least and most BPF fluctuation, respectively. However, in this case, there is little fluctuation in the BPF for both tests.

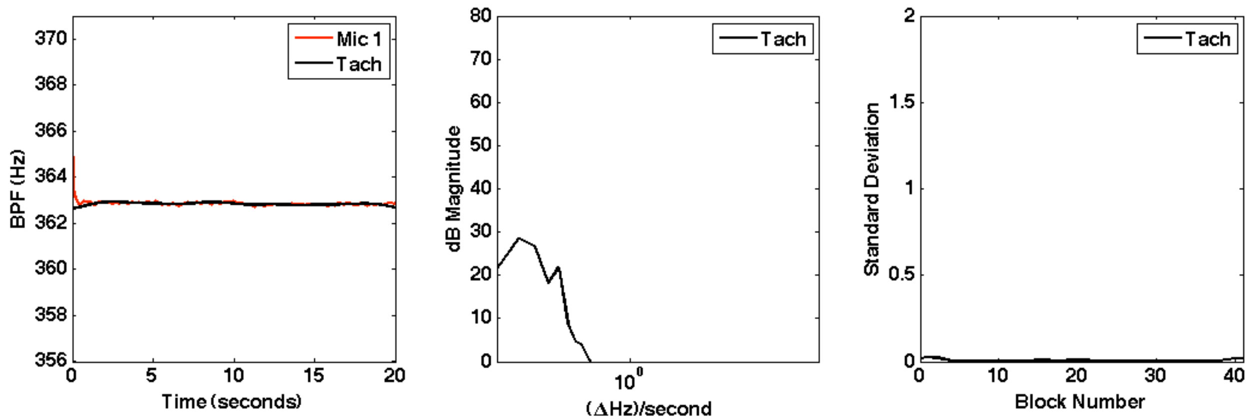


**Figure 5:** Low pressure and low speed case: Fan #3, 0 Pa pressure drop, 60% duty cycle PWM signal

BPF vs. time (left), FFT of BPF vs. time (middle), Standard deviation of BPF vs. time (right)

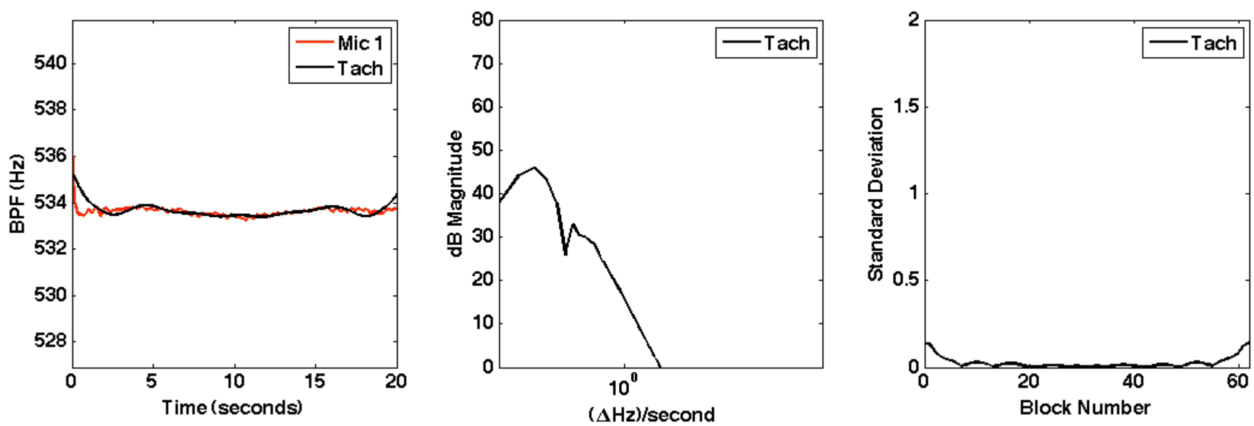


**Figure 6:** High pressure and high speed case: Fan #3, 24.9 Pa pressure drop, 80% duty cycle PWM signal

BPF vs. time (left), FFT of BPF vs. time (middle), Standard deviation of BPF vs. time (right)

## B. Conclusions

In all cases studied, the microphone, internal tachometer, and photo tachometer followed similar trends. The error microphones and the photo tachometer can be seen in the left-most plots in all of the above figures. In all cases, there are slight differences in the error microphone and the photo tachometer signals, but there is no apparent delay, which suggests that the error microphones are tracking the actual BPF of the fan quickly enough to be used effectively as error sensors. In all cases, the internal tachometer was not displayed because it followed almost perfectly the photo tachometer. This suggests that the internal tachometer tracks well enough to be used as a reference signal in feed-forward active noise control applications. It also suggests that the coherence of the error signals and the reference signal should not be affected by BPF fluctuations.

It is apparent that some fans experience more BPF fluctuations than others. However, it has not been shown that one specific parameter accounts for this in all cases. Most fans studied were similar in construction, yet they performed differently in similar circumstances. It was shown that, in specific cases, the speed of the fan and the pressure drop across the fan affected the steadiness of the BPF. However, this did not have a noticeable affect in all cases, so it cannot be said, definitively, that either of these factors affects BPF fluctuations in all cases. One specific motivation for this research was to study the effect of a pulse-width modulated driving mechanism on BPF fluctuations. The first and third cases above show that, while the speed of the fan can affect BPF fluctuations, it does not always affect it in cases with a PWM driving mechanism.

While it cannot be conclusively stated how much the steadiness of the BPF will be affected by specific parameters, it has been shown that some fans are steadier than others. For applications in which a fan's speed must be constant, methods have been presented to analyze BPF fluctuations over time.

## 4. FUTURE WORK

Future work will be done to study the effect of volumetric flow on BPF fluctuations. Subjectively, the fans with the most BPF fluctuation appeared to move more air, and quantitative measurements will be taken to show if this is true for all cases. Acoustic measurements will also be taken of the fans. This will show if noise from a fan that shows minimal BPF fluctuations can be attenuated further through active control.

## References


1. K.L. Gee and S.D. Sommerfeldt, "Application of Theoretical Modeling to Multichannel Active Control of Cooling Fan Noise," *J. Acoust. Soc. Am.* **115**(1), 228-236 (2004).

2. G.C. Lauchle and J.R. MacGillivray, and D.C. Swanson, "Active Control of Axial-Flow Fan Noise," *J. Acoust. Soc. Am.* **101**(1), 341-349 (1997).

3. D.A. Quinlan, "Application of Active Control to Axial Flow Fans," *Noise Control Engineering Journal* **39**(3), 95-101 (1992).

4. L. Vicente and E. Masgrau, "Fast convergence algorithms for active noise control in vehicles," *Proceedings of Joint ASA/EAA/DEGA Meeting, Berlin* (1999).

5. M. Rupp and A. H. Sayed, "Modified FXLMS algorithms with improved convergence performance," *IEEE Proceedings of ASILOMAR-29* (1995).

6. K.L. Gee and S.D. Sommerfeldt, "A Compact Active Control Implementation for Axial Cooling Fan Noise," *Noise Control Eng. J.*, **51**(6), 325-334 (2003).

7. G.C. Maling, "Noise Generated by Small Air Moving Devices," *Inter-Noise* **75**, 275-282 (1975)

8. P.G. Craven, "Antialias Filters and System Transient Response at High Sample Rates," *J. Audio Eng. Soc.*, **52**(3), 216-238 (2004).

9. C.A. Corral and C.S. Lindquist, "Design for Optimum Classical Filters," IEEE Proc. - Circuuits Devices Syst., **149**(516), 291-300 (2002).

10. D.W. P. Thomas and M.S. Woolfson, "Evaluation of Frequency Tracking Methods," IEEE Transactions on Power Delivery, **16**(3), 367-371 (2001).

11. N. Bom and B.W. Conoly, "Zero-Crossing Shift as a Detection Method," *J. Audio Eng. Soc.*, **47**(5), 1408-1411 (1969).