ELECTRONIC POP PROTECTION FOR MICROPHONES

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ABSTRACT

Pop noise caused by plosives generated by talkers, singers and other vocalists has long been a topic of interest to microphone manufacturers. The articulation of speech plosives (oral-stop consonants such as p, t, and k) can severely degrade the quality of a recording or performance. This is especially true for pressure-differential microphones, where not only is the unwanted artifact heard, but also there is the high potential for either microphone or associated electronics overload. Traditional wind/pop shields made of foam or a stretched fabric have been in use for many years, and are adequate for most common applications. However, it may be desired or advantageous to use an electronic version of pop protection under conditions where a pop or wind screen is not practical or sufficient, such as when using a lapel or podium microphone that is designed to be visually unobtrusive.

The results presented in this paper describe a relatively simple procedure to reduce microphone sensitivity to speech plosives via physically-informed signal processing methods, or Electronic Pop Protection (EPP). The EPP system itself comprises two parts: 1) detection of the presence of pop (turbulent air-jet flow) in the signal, and 2) suppression of this transient noise. A DSP-based demonstrator was created to illustrate and measure the operation of the algorithm on actual hardware. Finally, an objective evaluation of the algorithm is presented.

1. INTRODUCTION

For many years, wind-noise sensitivity of microphones has been a major problem for outdoor recordings. A related problem is the susceptibility of microphones to the speech jet, or flow of air from the talker's mouth from speech plosives. Recording studios typically rely on special pop screens that either cover the microphone or are placed between the mouth and the microphone. For outdoor recording situations where wind noise is an issue, microphones are typically shielded by foam or thick fuzzy materials. The purpose of the windscreen is to eliminate the airflow over the active microphone element, but allow the desired acoustic signal to pass without any modification.

This paper describes a new technique that uses the acoustic output signal from multiple microphones to determine the component of pickup signal that is due to turbulent flow (or other pressure fluctuations propagating at speeds much less than the speed of sound), and attempts to suppress it The basic idea exploits the knowledge that wind and pop-noise signals: 1) are caused by convective airflow whose speed of propagation is much less than that of desired propagating acoustic signals, and 2) exhibit a rapid decrease in correlation versus distance. As a result, the difference in the output powers of summed and subtracted signals of closely-spaced microphones can be used to estimate the ratio of slowly moving propagation relative to acoustic propagation. This estimate can then be utilized to drive a time varying suppression filter that is tailored to reduce noise signals having much lower propagation speeds than sound or are independent between channels.

Once detected, the suppression of unwanted pop-and wind-noise can be accomplished with various suppression schemes, one of which is presented. A simplified version of the pop protection algorithm was implemented with an array of two closely-spaced acoustic pressure microphones for detection, a professional differential microphone, and associated DSP hardware to compute the detection and apply the suppression scheme in real-time. A set of measurements of the algorithm's performance on this real-time hardware demonstrator is presented in a later section, using a metric for "pop sensitivity".

2. TURBULENT WIND-NOISE MODELS

The subject of modeling turbulent fluid flow has been an active area of research for many decades. Due to the complexity of the equations of motion describing turbulent fluid flow, only rough approximations and relatively simple statistical models have been suggested to describe this complex chaotic fluid flow. One extremely simplistic but useful model that describes the coherence of the pressure fluctuations in a turbulent boundary layer along the plane of flow is due to Corcos [1]. Although this model was developed for turbulent pressure fluctuation over a rigid half-plane, we have found that the simple Corcos model can be used to express the amount of spatial filtering of the turbulent jet from a talker. Thus we will use this model to predict the spatial coherence of the turbulence for both speech jets as well as free-space turbulence.

The spatial characteristics of the pressure fluctuations can be expressed by the space-frequency cross-spectrum function,

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$$G_{p1p2}(\psi,\omega)=\int_{-\infty}^{\infty}R_{p1p2}(\psi,\tau)e^{-j\omega\tau}d\tau \qquad (1)$$

where ψ represents the spatial dimension, ω the angular frequency, τ the temporal dimension, and R is the cross-correlation function between the microphone pair. The magnitude coherence function is defined as the normalized cross-spectrum by the autospectrum of the two channels as,

$$\gamma(r,\omega)=\frac{\left|G_{p1p2}(\omega)\right|}{\left[G_{p1p1}(\omega)G_{p2p2}(\omega)\right]^{1/2}} \qquad (2)$$

It is known that large-scale components of the pressure field lose coherence slowly during the convection with free-stream velocity U while the small-scale components lose coherence in distances proportional to their wavelengths. Corcos assumed that the stream-wise coherence decays spatially as a function of the similarity variable $\omega r/U_c$, where U_c is the convective speed and is typically related to the free-stream velocity U as, $U_c = 0.8U$. The Corcos model can be mathematically stated as:

$$\gamma(r,\omega)=\exp\left(\frac{-\alpha\omega r}{U_c}\right) \qquad (3)$$

where α is an experimentally determined decay constant,

$\alpha = 0.125$, and r is the displacement (distance) variable.

3. POP-NOISE IN DIFFERENTIAL MICROPHONES

Since n-th order differential transducers (e.g. directional microphones) have responses that are proportional to the n-th power of the wavenumber, these transducers are very sensitive to high-wavenumber acoustic propagation. One acoustic field that has high-wavenumber acoustic propagation is in turbulent fluid flow where the convective velocity is much less than the speed of sound. For wind and pop noise, the difference between propagating speeds is typically by two orders of magnitude. As a result, for convective turbulence and propagating acoustic signals at the same frequency, the wave-number ratio will differ by two orders of magnitude. Since the sensitivity of differential microphones is proportional to k^n, the output signal ratio of turbulent signals will be two orders of magnitude greater than the propagating acoustic signals for equivalent levels of pressure fluctuation. As shown in Section 2, the coherence of the turbulence decays rapidly with distance, thus the differential pressure signal power ratio between the turbulent and propagating signals is even larger than the ratios of the convective to acoustic propagating speeds.

4. POP NOISE DETECTION AND SUPPRESSION

4.1. Detection

The goal of incoherent noise and turbulent wind and pop-noise detection is to determine what frequency components are due to noise and/or turbulence and what components are desired acoustic signals. As already stated, the proposed noise signal detection and suppression algorithm is based on the ratios of the sum and difference signal powers. For two closely spaced omni-directional microphones, the ratio of the difference of power spectra to the sum of the power spectra is substantially different for turbulent and acoustic flows. If this measured ratio, calculated from the detection microphone pair signals, is greater than the maximum predicted for acoustic signals (signals propagating along the axis of the microphones), then the signal is declared noise and/or turbulence and is used to update the noise estimation and suppression.

As a result, it is possible to detect whether the acoustic signals picked-up by the microphones are turbulent-like noise or propagating acoustic signals by comparing the sum and difference powers. Figure 1 shows the difference-to-sum power ratio for a pair of omnidirectional microphones spaced at 2 cm in a convective fluid flow propagating at 5 m/s. It can be seen in this figure that there is a relatively wide difference between the acoustic and turbulent sum-difference power ratios. The ratio differences become more pronounced at low frequencies since the differential microphone rolls of at -6dB/octave, where the predicted turbulent component rolls off at a much slower rate.

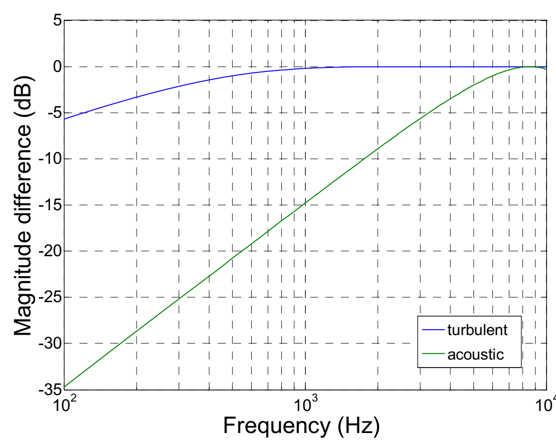

Figure 1: Acoustic and turbulent difference-to-sum power ratio

Note that it has been assumed that the coherence decay is similar in directions that are normal to the flow. The closest the sum and difference powers come to each other is for acoustic signals propagating along the microphone axis. Therefore, we can be assured that the measured power ratio for acoustic signals is less than or equal to the power ratio for acoustic signals arriving along the microphone axis. This limiting approximation is the key to our proposed noise detection and resulting suppression of signals that are identified as turbulent and/or noise.

4.2. Suppression

After detecting the presence, and to some extent, the degree of turbulent noise at the transducer, one of many possible suppression schemes can be applied. One such implementation (that is directly related to a Wiener filter solution), is to utilize the estimated coherence function between pairs of microphones to generate a coherence-based gain function to attenuate turbulent components.

There is a relatively large difference in the coherence values for propagating sound fields and turbulent fluid flow. The large difference suggests that one could weight the resulting spectrum of the microphone output by either the coherence function itself or some weighted or processed version of the coherence. Since the coherence for propagating acoustic waves is essentially unity, this weighting scheme will pass the desired propagating acoustic signals. For turbulent propagation, the coherence (or some processed version) is low and weighting by this function will diminish the system output. A major limiting factor to using the coherence function is that pop noise tends to be a highly transient event, and the required ensemble averaging while estimating the coherence function can significantly underestimate the coherence.

One possible weighting function would be to enforce the sum and difference power ratio that would exist for propagating acoustic signals that are traveling along the axes of the microphones. The fluctuating pressure signals traveling along the microphone axes for both microphones can be written as,

$$p_1(t) = s(t) + v_1(t) + n_1(t) \tag{4}$$

$$p_2(t) = s(t-\tau_s) + v_1(t-\tau_v) + n_2(t) \tag{5}$$

where τ_s is the delay for the propagating acoustic signal $s(t)$, τ_v is the delay for the convective or slow propagating waves $v(t)$, and $n_1(t)$ and $n_2(t)$ represent microphone self-noise and/or incoherent turbulent noise at the microphones. If we represent the signals in the frequency domain, the power spectrum of the pressure sum ($p_1(t)+p_2(t)$) can be written as,

$$\begin{aligned} G_{++}(\omega) &\approx 4G_{ss}{}^2(\omega) + 4G_{\aleph\aleph}(\omega)\gamma_c{}^2(\omega) + \ldots \\ &2G_{\aleph\aleph}(\omega)[1-\gamma_c{}^2(\omega)] + \ldots \\ &G_{N_1N_1}(\omega) + G_{N_2N_2}(\omega) \end{aligned} \tag{6}$$

and for the difference signals ($p_1(t) - p_2(t)$) the output power spectrum can be written as,

$$\begin{aligned} G_{--}(\omega) &= 4G_{ss}(\omega)\sin^2(\frac{\omega d}{2c}) + \ldots \\ &4G_{\aleph\aleph}(\omega)\gamma_c{}^2(\omega)\sin^2(\frac{\omega d}{2U_c}) + \ldots \\ &G_{\aleph\aleph}(\omega)[1-\gamma_c{}^2(\omega)] + G_{N_1N_1}(\omega) + G_{N_2N_2}(\omega) \end{aligned} \tag{7}$$

The ratio of these factors (denoted as R), gives the expected power ratio of the difference and sum signals between the microphones,

$$R(\omega) = \frac{G_{--}(\omega)}{G_{++}(\omega)} \tag{8}$$

where $\gamma_c(\omega)$ is the turbulence coherence as measured or predicted by the Corcos or other turbulence models, $G_{\aleph\aleph}(\omega)$ is the power spectrum of the turbulent noise (assumed here to be the same at both microphones), d is the sensor spacing, c is the speed of sound, and $G_{N_1N_1}(\omega)$ and $G_{N_2N_2}(\omega)$ represent the power spectrum of the independent noise at the microphones due to sensor self-noise. For turbulent flow where the convective wave speed is much less than the speed of sound, the difference between the sum-signal power and the difference-signal power will be much less than for acoustic signals (by approximately the ratio of propagation speeds) and thereby moves the power ratio to unity. Also, as discussed earlier, the convective turbulence spatial correlation function decays rapidly and this term becomes dominant when turbulence (or independent sensor self-noise) is present and thereby moves the power ratio towards unity. For a purely propagating acoustic signal traveling along the microphone axis, the power ratio R is,

$$R_a(\omega) = \sin^2\left(\frac{\omega d}{2c}\right) \tag{9}$$

The results shown in equations 8 and 9 lead to a very simple algorithm for suppression of airflow turbulence and sensor self-noise. The rapid decay of spatial coherence or large difference in propagation speeds, results in the relative powers between the sums and differences of the closely-spaced pressure (zeroth-order) microphones to be much smaller than for an acoustic planewave propagating along the microphone array axis.

Thus, a proposed suppression gain $S(\omega)$, can thus be simply stated as: if the measured ratio exceeds that given by Eq. 9, then the output signal power is reduced by the difference between the measured power ratio and that predicted by Eq. 9. The equation that implements this gain is,

$$S(\omega) = \frac{R_a(\omega)}{R_m(\omega)} \tag{10}$$

where $R_m(\omega)$ is the measured sum and difference signal power ratio. It should be noted that the techniques described above require that the microphone elements be fairly closely matched in both amplitude and phase. Calibration between closely-spaced pressure microphones is critical for the detection of wind turbulence using sum and difference signals.

5. MEASUREMENT AND EVALUATION

A performance analysis of the algorithm using a simplified suppression scheme was conducted using the real-time DSP-based hardware demonstrator. To objectively determine what amount of additional protection is provided by EPP, the Equivalent Pop Level (EPL) was measured for the microphone under various conditions. The EPL metric is essentially a measure of "pop sensitivity" [3-6].

$$EPL = 20\log_{10}\left(\frac{V_{pop}}{V_{sens}}\right) + 94 \text{ dB SPL} \tag{11}$$

where V_{pop} is the measured output voltage due to pop stimulus, and V_{sens} is the output voltage at 1 kHz, 1 Pa. The EPL was computed from measurements of a Sennheiser pressure-differential microphone under the following conditions:

1) Without any physical or electronic pop protection
2) With electronic pop protection only
3) With a small physical windshield only
4) With a small physical windshield *and* EPP
5) With a larger physical windshield only
6) With the larger physical windshield *and* EPP

The primary outcome of these measurements is a single measure of pop sensitivity – the EPL – for each of the different conditions measured. The graph below summarizes this data.

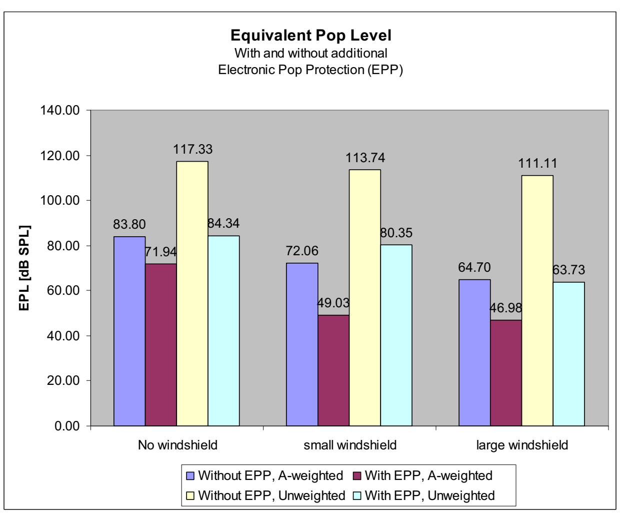

Figure 2: EPL data with various pop protection technologies

The increase or decrease in pop sensitivity as measured by the EPL seems to correlate to our perception of an increase or decrease in the "pop effect," for the stimuli used. This of course, does not imply that the same perceptual correlation holds for different stimuli (e.g. voice). However, it does imply that the EPL measurement data taken here is correlated to our subjective analysis of the pop under the measurement conditions.

6. CONCLUSIONS

This paper has proposed a simple technique to detect air flow turbulence, slowly propagating signals, and incoherent noise in microphone array systems, for the specific purpose of reducing the "pop sensitivity" of pressure-differential microphones. The idea utilizes the measured power ratio of difference and sum signals between closely-spaced microphones. Since the ratio of the difference to sum signal powers is large (near unity) when turbulent air flow, slowly propagating signals, or independent self-noise is present and small (much less than 1) while desired acoustic signals are present, one can easily detect turbulence or relatively high-wavenumber low-speed fluid perturbations.

A physically-based informed suppression scheme (based on a simple measure related to the coherence between a closely-spaced microphone pair) for turbulence reduction was derived and other ad-hoc schemes described. Experimental results were shown where the reduction of wind noise turbulence was more than 20 dB. The Electronic Pop Protection scheme described has been shown to be an effective solution in reducing the pop sensitivity of pressure-differential microphones, and may find use whenever there is a need for increased pop protection, lack of space for traditional foam shields, or aesthetic constraints.

7. REFERENCES

[1] G. M. Corcos, *The structure of the turbulent pressure field in boundary layer flows*, J. Fluid Mech., 18: pp 353-378, 1964.

[2] IEC 60268-4 Sound System Equipment – Part 4: Microphones, 2004

[3] M. Schneider, "Pop Measurement, Low-Frequency Response and Microphone Construction", 104th AES Convention, 1998

[4] M. Schneider, "Transients in Microphones: Pop and Impulse", Proc. Of the AES UK Conf.: Microphones and Loudspeakers: The Ins and Outs of Audio, London, UK, 1998

[5] W. Wienhöfer, & J. Sennheiser, Measuring Equipment for the Estimation of "Pop" Sensitivity of Microphones. J. Audio Eng. Soc., Vol. 36, No. 6, June 1988

[6] G. W, Elko, "Reducing Noise in Audio Systems", US Patent No. 7171008, January 30, 2007.