VIRTUAL ERROR SENSING FOR ACTIVE NOISE
CONTROL IN A ONE-DIMENSIONAL WAVEGUIDE:
PERFORMANCE PREDICTION VS MEASUREMENT

Abbreviated Title: Real time virtual error sensing

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Abstract

Virtual error sensing is a novel active noise control technique, which is designed to produce a zone of attenuation remote from the physical error sensors. In this paper virtual sensing is investigated for tonal noise (both on and off resonance) in a long narrow duct. The performance of the virtual error sensors using real-time control is compared to the performance determined from an analytical model and the performance determined through the post-processing of experimental data. Two examples of control using post-processed experimental transfer function data are presented; the first relied on transfer functions measured using broadband noise and the second relied on transfer functions measured at discrete frequencies. The results highlight the significant errors encountered as a result of using broadband transfer functions in lightly damped enclosures.

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I. INTRODUCTION

The use of a local active noise control system within a highly damped and modally dense enclosure can result in small "zones of quiet" around the error sensor. Therefore, for an observer to perceive any reduction in noise level, the error sensor must be placed in very close proximity to the observer’s head, which in many cases is impractical. The concept of "virtual" sensing, an active noise control technique where a local zone of quiet is created at a location remote from the error sensor was first introduced by Garcia-Bonito et al. [1]. Cazzolato [2] introduced a novel forward-difference extrapolation virtual sensing technique designed to adapt to any physical system changes. Two virtual error sensing algorithms were developed to predict the sound pressure at the observer location. The techniques were applied to control tonal noise in a long narrow duct model and the results were validated with experimental data [3]. However, in both cases, control performance was evaluated by quadratic optimisation of the post-processed transfer function data. Here, the results of real-time active noise control using a feedforward controller with hard-wired virtual error sensors are compared to results obtained using transfer function data. It will be shown that the reason for the poor experimental performance observed by Kestell et al. [3] was almost entirely due to the errors inherent in broadband transfer function measurements in a lightly damped enclosure.
II. THEORY

At low frequencies, when the distance between the transducers making up the virtual sensor is much less than a wavelength, the spatial rate of change of sound pressure is low and therefore predictable [4]. Hence, by fitting a straight or curved line between the pressures, $p_1$, $p_2$ and $p_3$ measured at fixed locations, the pressure, $p_v$ at a remote location can be estimated (Figure 1). The two forward-difference virtual microphone algorithms are summarised below.

1. Two microphone, linear prediction:

$$p_v = \begin{bmatrix} \frac{x}{h} & 1 \end{bmatrix} \begin{bmatrix} 0.5 & -0.5 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} p_2 \\ p_1 \end{bmatrix} \tag{1}$$

2. Three microphone, quadratic prediction:

$$p_v = [ \left( \frac{x}{h} \right)^2 \frac{x}{h} 1] \begin{bmatrix} 0.5 & -1.0 & 0.5 \\ 1.5 & -2.0 & 0.5 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} p_3 \\ p_2 \\ p_1 \end{bmatrix} \tag{2}$$

where $p_v$ is the pressure at the observer location, $x$ is the distance between the observer and the nearest sensor, $p_1$, $p_2$ and $p_3$ are the measured pressures and $h$ is the separation distance between the transducers for the quadratic prediction and is equal to 25 mm. The separation distance between the two microphones in the linear prediction is $2h$. For a full derivation of the prediction equations see [4].
III. EXPERIMENT

The results for real-time control in the duct were compared to the results obtained using both the analytical model and post-processed experimental data. A primary noise source was positioned at one end of the duct with a control source located 0.5m from the opposite end (Figure 2). The sound pressure profile around the virtual sensors was observed over a 0.5m length with 21 equally spaced measurement locations. The duct was rigidly terminated and had a resonance quality factor, Q, of approximately 50.

The analytical model of the duct was evaluated using MATLAB. Transfer functions between the primary and secondary source and the 21 measurement locations were calculated using classical theory [5] in which the first 25 modes were considered.

For the post-processed results, transfer functions were measured between the two sources and the 21 measurement locations. Two types of post-processed results are presented here; calculations based on broadband transfer functions measured using random noise and calculations based on discrete frequency transfer functions measured using discrete tones corresponding to a specific resonance frequency. The broadband transfer functions were measured from 0 to 400 Hz with a sampling frequency of 1024 Hz and a bandwidth of 0.5 Hz.

The data (measured and simulated) were then post processed and the cost function minimised using quadratic optimisation, which incorporated a 1% error (40 dB control limit) to simulate the errors expected in a real-time controller.

The real-time experiments discussed here were conducted using the Causal Systems EZ-ANCII feedforward controller.
IV. RESULTS FOR RIGIDLY TERMINATED DUCT

Figure 3 shows the results obtained when controlling an acoustic resonance in a long, narrow, rigidly terminated duct. The vertical lines represent the sensor locations and the solid circle represents the observer location. The top curve without any circles represents the uncontrolled primary field. The other curves represent the controlled sound field at increasing separation distances between the observer and the sensors. The distance between the observer and the sensors is indicated by the distance between the right most vertical line and the solid circle located on the curve. Figures 3(a), (b), (c) and (d) show a comparison of the performance of the four control evaluation methods using the linear virtual microphone. Analytical control shows an attenuation of approximately 40 dB at all separation distances due to the artificial 1% error applied to the calculated optimal control source strengths. The post-processed tonal, broadband control and the real-time control all show a decrease in attenuation as the separation distance between the transducers and the observer location is increased to $4h$. Control using the tonal experimental transfer function compares more favourably to the theory than the other experimental examples with 37 dB attenuation at an observer/sensor separation distance of $4h$. The post-processed control using broadband transfer function data performed the worst with 19 dB of attenuation at $4h$, while the real-time control achieved an attenuation of 25 dB at $4h$.

It can therefore be concluded that the performance of the control obtained using post-processed transfer function measurements obtained with broadband noise in a lightly damped enclosure is affected by errors associated with the use of the fast fourier transform used to calculate the frequency response functions. These errors are greatest when the coherence is low, occurring at resonances and anti-resonances. The poor coherence at the anti-resonances is a result of low signal to noise ratio. The coherence is lowest at resonance which is due to spec-
tral leakage, even though this was minimised by using a Hanning window and a large number of points in the FFT (2048). In heavily damped enclosures leakage is generally not a problem when measuring broadband transfer functions since the resonant peaks are broader (than in a lightly damped enclosure). Using tonal noise to measure the transfer functions eliminates the low coherence caused by leakage in a lightly damped enclosure, consequently resulting in higher levels of predicted attenuation as a result of active noise control, for all separation distances.

Unlike the post-processed data, which used a single microphone, the real-time measurements used a minimum of two microphones. Sensitivity and phase mismatch between the sensors used in real-time experiments limited the performance.

Figure 4 shows the performance of the quadratic virtual microphone for the four different control strategies. The analytical model shows an attenuation of 40 dB for all separation distances. Note that this is an artificial limit imposed to simulate the expected limitations of a real-time controller. Similar to the linear virtual microphone, the real-time control example also achieves greater attenuation than the post-processed control using broadband transfer function data for all separation distances. Control using post-processed tonal transfer function data was much better than that achieved by the other two experimental control examples with 33 dB attenuation at 4h.

Comparing the quadratic virtual microphone control examples with the corresponding linear control examples shows that the linear algorithm out-performs the quadratic algorithm with the exception of the analytical models. This is due to the presence of short wavelength spatial variations in the experimental data (see Figure 5) as suggested by Kestell et al. [3]. Consequently, quadratic predictions are less accurate than the linear estimates when using physical data. The real-time experiment used three microphones and matching both phase and magnitude sensi-
tivities was very difficult and consequently the pressure estimate at the virtual location was
degraded.

The experiments presented here were also repeated at an acoustic anti-resonance. Conclu-
sions drawn from the results of those experiments agreed with all of the conclusions presented
here. These results can be found in [6].

V. CONCLUSIONS

The performance of two forward-difference prediction virtual algorithms using real-time
control in a long, narrow, rigid-walled duct has been evaluated. The results are in agreement
with those of Kestell et al. [3] and suggest that these forward-difference virtual microphones
can be successfully implemented in a real-time feedforward control situation.

Results obtained using post-processed transfer function data with random noise excitation
in a lightly damped enclosure were significantly affected by inherent FFT errors. This implies
that tonal excitation should be used to obtain transfer function data for use in predicting the
expected performance of an ideal real-time controller. Alternatively, the FFT bin width needs
to be larger than the inverse of the decay time.

In practice, the performance of real-time control is influenced by phase and sensitivity mis-
mash between the prediction transducers. Thus accurate system calibration and transducer
selection is important. The linear prediction algorithm out-performed the quadratic prediction
algorithm, which confirms that the quadratic algorithm is more sensitive to short wavelength
spatial variations.

In the reactive environment in which these experiments were conducted, the spatial distri-
bution of the sound field at resonance is determined by the mode shape or eigenfunction. This
is in fact a sinusoid and therefore in this environment the possible prediction method could be a sinusoidal extrapolation. This could form the basis for future work.

Work to improve the prediction algorithm and reduce the effect of short wavelength extraneous noise has begun and involves using higher order microphone arrays, containing redundant microphones.


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