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IN-DUCT MEASUREMENT OF GAS TURBINE NOISE EMMISIONS USING A CROSS SPECTRUM METHOD

M.P. Sacks/Tacet Engineering Ltd.

J.G. Kawall/Ryerson Polytechnic University,
Toronto, Ontario, Canada

R. Behboudi/ Tacet Engineering Ltd.

J. Buttell/Higgot-Kane Industrial Noise Controls Ltd.

ABSTRACT

It is often desirable to measure the sound power radiated by the inlet or exhaust of a gas turbine in an installation that includes filters and silencers. A direct measurement can only be accomplished within the empty duct between the inlet or exhaust flange and the silencer. For a number of reasons ISO 5136 [1] cannot be used directly to perform these measurements. Consequently, some other means must be found.

The primary requirement for an in-duct sound power measurement is a valid in-duct sound pressure measurement. In order to accomplish this, the effect of the turbulent pressure fluctuations inherent in the flow, or induced by the microphone probes, must be removed from the dynamic pressure signals sensed by the microphone.

This paper describes the use of a two-microphone cross amplitude spectrum (CAS) technique to perform accurate measurements of the autospectra of sound fields embedded in turbulent duct flows. This technique is based on the assumption that the acoustic and turbulence signals detected by any microphone are uncorrelated with each other and also with the turbulence signals detected by another microphone.

The paper gives the measurement parameters required for various degrees of turbulence rejection as well as the accuracy and convergence of the estimate of the embedded acoustic spectrum. The paper also provides a means to determine the microphone separation distance required to ensure that the turbulence signals at the two microphones are uncorrelated. These results are based on both the simulation of acoustic fields embedded in turbulence and on laboratory experiments using both loudspeakers and an aeroacoustic wind tunnel.

Typical results show that for practical measurement durations the proposed method will provide a turbulence rejection in octave bands of approximately 15 dB at 31.5 Hz rising smoothly to 25 dB at 8 kHz. The method thus appears to have some distinct advantages over ISO 5136 methodology.

INTRODUCTION

The fundamental assumption of the cross amplitude spectrum (CAS) technique is that the turbulence pressure fluctuations sensed by the two microphones are uncorrelated. The purpose of this paper is to establish that we would expect this assumption to be true in typical applications and then to describe a series of laboratory experiments designed to investigate the efficacy of the CAS technique in extracting sound spectra embedded in noise.

In order to ensure that the turbulence pressure fluctuations sensed by the two microphones are uncorrelated, the cross-stream distance between the mic locations must exceed the spatial integral scale of the turbulence field within the duct in which the sound is generated. Experimental results (e.g. [2], [3], [4]) serve to establish that, for turbulent flow within a typical duct, the integral scale in question is significantly less than the hydraulic diameter of the duct. Accordingly, once the mics are separated by a cross-stream distance greater than, say, 50% of the duct hydraulic diameter, the turbulence pressure fluctuations at the mic locations will be uncorrelated, as required.

It is clear that at any given duct cross section there will be no difficulty in finding mic locations that satisfy the above criteria; e.g. flush mounted microphones on opposite walls of a square duct.

The acoustic pressure fluctuations measured by the two microphones can be expected to be fully correlated, i.e. a coherence function of unity at all frequencies for which the acoustic signal exists.

Consequently, we expect the dynamic pressure field within the duct to consist of the superposition of a correlated acoustic pressure signal and an uncorrelated turbulence pressure signal.

We can mimic this situation in the laboratory by using loudspeakers to produce the correlated and uncorrelated signals at various intensities and masking levels and thereby identify some typical properties of the CAS technique.

TEST PROCEDURE

A number of experiments were performed using the following procedure:

1. Two remote rooms were selected and a calibrated microphone placed in each room.
2. A loudspeaker was placed near each microphone. Both loudspeakers were identical and were driven by a two-channel amplifier fed by a single electronic sound source. The sound signals produced represent the correlated signals and their cross spectrum amplitude represents the target spectrum.
3. A second loudspeaker was also placed near each microphone. Both of these loudspeakers were driven by their own amplifier and electronic sound source. These sound signals represent the uncorrelated signals that were used to mask the correlated signals. The masking signals were typically 10 dB or more louder than the corresponding correlated signals.

All sound sources used were broad band and either random or pseudo random. The four signal levels could be adjusted independently. The correlated and uncorrelated signals were recorded separately and in combination. A dual channel, 16 bit A/D system was used to record the data which was stored on a computer hard drive for post processing.

All data was collected at a rate of 16,000 samples/second and analyzed in blocks of 8192 samples providing a frequency resolution of 1.953 Hz which corresponds to a block duration of 0.512 seconds. Approximately 8.5 minutes of data is required for 1000 data blocks which results in more than 8 million samples per channel and a file storage size of approximately 32 MB.

Two techniques were used to analyze the raw data into the octave band values that are reported herein. First the auto and cross spectra are obtained by block averaging in the frequency domain. Next variable smoothing is used to further average the data within each frequency band. This process involves averaging a number of points, replacing the first value with the average, moving forward one point and repeating the process throughout the octave band. The 31.5 Hz O.B. uses no smoothing, the 63 Hz O.B. uses 2 point smoothing with each subsequent band doubling until we have 256 point smoothing in the 8kHz O.B.

EXPERIMENTAL RESULTS

We report on the results of three experiments below. Table 1 shows the overall sound pressure level at each microphone in each experiment for the correlated, uncorrelated and combined signals.

	Correlated		*Uncorrelated*		**Combined**	
Exp.	**MIC 1**	**MIC 2**	*MIC 1*	*MIC 2*	**MIC 1**	**MIC 2**
1	85.2	85.3	*96.8*	*97.0*	97.1	97.4
2	88.4	72.4	*97.2*	*97.1*	97.8	96.7
3	100.3	90.2	*107.8*	*99.2*	108.5	99.7

Table 1 – Total Sound Pressure Levels

Tables 2, 3 and 4 show the results of experiments 1, 2 and 3, respectively, with block averaging. The values in the tables are the total sound pressure levels of the signals in decibels re 20 μPa. The values in the "X-Spectrum" column are for no smoothing except for 10,000 averages which represents 1000 block averages followed by a 10 point running average; i.e. constant smoothing. The "V. Smoothing" column shows the results for variable smoothing.

The "Uncor Signal" results show the decrease in the cross spectrum amplitude (i.e. the rejection) of the uncorrelated signals with averaging. These results show a decrease of approximately 5 dB in total level for each factor of ten increase in the number of averages.

For the correlated signals, the "Cor. Signal" results are shown for 100 averages only since these spectra change very little after 10 averages. Typical ambient levels during the experiments are shown for reference.

We note that the cross spectrum amplitude of the correlated signals is equal to the average of the two autospectra amplitudes. This result is expected from theoretical considerations (e.g. ref [4]). Since we are primarily interested in the average level of the two microphones, rather than the level at each microphone independently, the cross spectrum amplitude of the two correlated signals becomes the target spectrum to which the cross spectrum amplitude of the combined signals must converge if the CAS method is to be useful.

We see that in all three experiments the cross spectrum amplitude of the combined signals converges to the target sound pressure level with sufficient averaging. The advantages of variable smoothing over no smoothing are apparent from the tabulated data. With variable smoothing, in experiments 1 and 3, the target level is achieved after 100 averages. This is clear from the fact that 1000 block averages produces no further change in the cross spectrum amplitude of the combined signal. For experiment 2 the target level is achieved only after 1000 averages. This is due to a low signal to noise ratio at microphone 2 as shown in Table 1.

Typical octave band results are shown in Figures 1 to 5 for experiment 3.

Figure 1 shows the octave band autospectra of both the correlated and combined signals at mic1 and mic2 and the cross spectrum of the correlated signal, i.e. the target spectrum.

Figure 2 shows the octave band autospectra of the uncorrelated signals at both microphones and the cross spectrum amplitude, for no smoothing, with averaging. It is clear that the trend of a 5 dB reduction for each factor of ten increase in the number of averages, as seen for the overall level, is also apparent for each of the octave bands.

Figure 3 shows the octave band autospectra and the cross spectrum amplitudes of the combined signals at mic1 and mic2 along with the cross spectrum amplitude of the correlated signal; i.e. the target spectrum. The results are shown as a function of averaging, variable smoothing not included. We see that convergence is rapid where the signal to noise ratio is high but that, in the two highest bands, the cross spectrum amplitude has not converged to the target values even after 10,000 averages; i.e. 1000 block averages and 10 point constant smoothing. This is due to the very low signal to noise ratio in these bands.

Figure 4 shows the same cross spectrum amplitude data as Figure 3 this time using variable smoothing. We see that the octave band estimates are greatly improved, particularly in the higher frequencies.

Figure 5 shows the cross spectrum amplitude data for 1000 averages in order to provide a direct comparison between variable smoothing and no smoothing.

DISCUSSION

Within the context of the experiments performed we have seen that the cross spectrum amplitude of two uncorrelated signals reduces by approximately 5 dB for each factor of ten increase in the number of block averages and that this result applies to individual octave bands as well as the overall level of the signal.

We have also seen that as the cross spectrum amplitude of the combined signal approaches the target, the rate of convergence slows down to something between 0 dB and 5 dB for each factor of ten increase in the number of averages.

Once the cross spectrum amplitude of the combined signal reaches the target there is no further change in the spectrum amplitude with additional averaging.

Consequently if the number of averages is increased by a factor of ten (say from 10 to 100) and the cross spectrum amplitude decreases by 5 dB, any embedded correlated signal is of the order of 10 dB or more below the higher estimate (e.g. for 10 averages).

Conversely, if the cross spectrum amplitude decreases by less than 5 dB for a ten times increase in the number of averages, then the embedded correlated signal is less than 10 dB below the higher estimate.

It appears from the data that if the cross spectrum amplitude decreases by approximately 1 dB for a ten times increase in the number of averages, then the embedded correlated signal levels are essentially recovered by the lower estimate.

We note that a limitation of the CAS technique will likely be the time required to record the data. This time is equal to the number of blocks to be averaged divided by the frequency resolution; e.g. if we decide that we want at least ten data points in the 31.5 Hz octave band, then the required frequency resolution is approximately 2 Hz. The time required for 1000 blocks is then approximately 500 seconds or 8.5 minutes; the time required for 10,000 blocks is 1.5 hours.

Test durations of the order of ten minutes are likely acceptable; durations of the order of 1.5 hours are likely not practical.

Data file size restrictions are likely to be less of an issue given the storage capacity of current computers.

CONCLUSIONS

1. The cross amplitude spectrum (CAS) technique provides an effective means of accurately measuring correlated signals embedded in uncorrelated noise.
2. For practical measurement durations the method is capable of extracting signals that are of the order of 15 dB to 20 dB below the uncorrelated masking noise.
3. The reduction of uncorrelated noise, e.g. turbulence rejection, is at least 15 dB for 1000 block averages and is independent of frequency.
4. The addition of variable smoothing increases the noise rejection by 0 dB in the 31.5 Hz O.B. which rises smoothly to at least 10 dB in the 8 kHz O.B.
5. The net uncorrelated noise rejection for 1000 block averages plus variable smoothing is therefore at least 15 dB in the 31.5 Hz O.B. which rises smoothly to at least 25 dB in the 8 kHz O.B.
6. The CAS method appears to offer the potential for higher turbulence rejection at low (below 70 Hz) and high (above 1000 Hz) frequencies than that of a commercially available turbulence screen [5]. In any event, such a device could not be used in a gas turbine exhaust duct.

ACKNOWLEDGMENTS

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[5] Bruel & Kjaer Product Data, Turbulence Screen UA 0436.

Avg.	Mic#1	Mic#2	CS,NS	CS,VS	Type
100	85.2	85.3	85.1	-----	Cor.
10	48.8	48.8	47.2	-----	Amb.
1	97.0	97.1	95.3	87.9	Uncor.
10	96.8	97.1	90.6	82.8	"
100	96.8	97.1	85.8	77.6	"
1000	96.8	97.0	80.9	73.5	"
10000	96.8	97.0	75.7	-----	"
1	97.2	97.6	95.7	89.2	Comb.
10	97.1	97.4	91.3	85.8	"
100	97.1	97.4	87.5	85.1	"
1000	97.1	97.4	85.6	85.1	"
10000	97.1	97.4	85.1	-----	"

Table 2 – Experiment 1

Avg.	Mic#1	Mic#2	CS,NS	CS,VS	Type
100	88.4	72.4	80.3	-----	Cor.
10	47.9	44.4	41.6	-----	Amb.
1	97.3	97.2	95.6	88.4	Uncor.
10	97.3	97.2	90.9	83.5	"
100	97.3	97.1	86.0	79.0	"
1000	97.3	97.2	81.2	74.3	"
10000	97.2	97.1	76.2	-----	"
1	97.9	96.8	95.7	88.7	Comb.
10	97.7	96.8	91.0	84.0	"
100	97.8	96.8	86.5	81.3	"
1000	97.8	96.8	82.6	80.5	"
10000	97.8	96.7	80.7	-----	"

Table 3 – Experiment 2

Avg.	Mic#1	Mic#2	CS,NS	CS,VS	Type
100	100.3	90.2	95.0	95.0	Cor.
10	54.3	63.4	55.5	-----	Amb.
1	107.7	99.1	102.3	95.7	Uncor.
10	107.8	99.2	97.8	91.0	"
100	107.8	99.2	92.8	85.7	"
1000	107.8	99.2	87.9	81.4	"
10000	107.8	99.2	83.1	-----	"
1	108.5	99.8	103.1	97.6	Comb.
10	108.5	99.7	99.2	95.6	"
100	108.5	99.7	96.5	95.0	"
1000	108.5	99.7	95.4	95.0	"
10000	108.5	99.7	95.0	-----	"

Table 4 – Experiment 3

Note:
The numbers in the first two columns of tables 2-4 represent the total unweighted sound pressure level in dB (re 20 μPa) as received at each microphone location, and columns 3 & 4 represent the cross amplitude spectrum between the two mic spectra without and with smoothing, respectively.

CS = Cross Spectrum
NS = No Smoothing (running average)
VS = Variable Smoothing
Cor. = Correlated Signal
Uncor. = Uncorrelated Signal
Amb. = Ambient Noise
Comb. = Combined signal
10000 avg. = 1000 FFT block avg. + 10 pt. constant smoothing

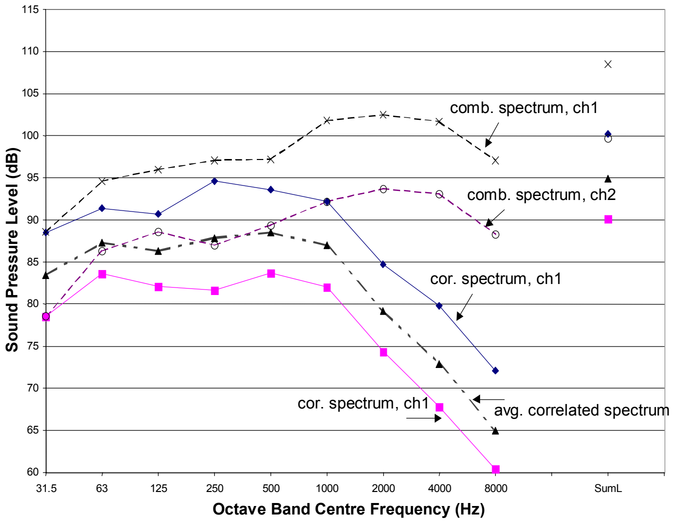

Figure 1 – Combined and Correlated Spectra, Experiment 3

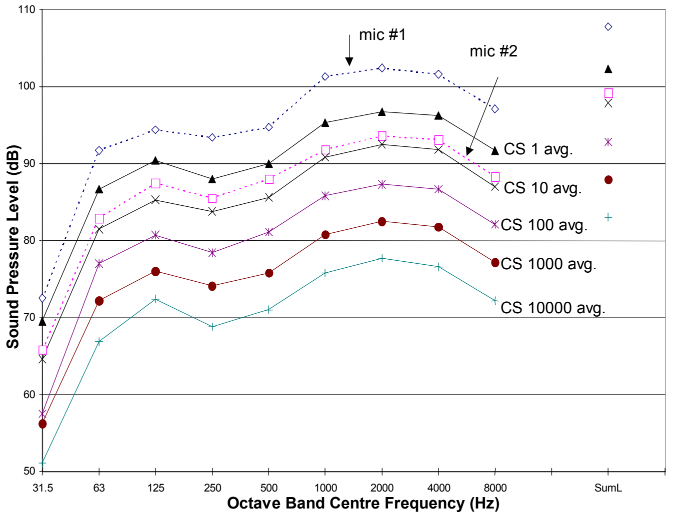

Figure 2 – Cross Amplitude Spectrum of the Uncorrelated Signals (experiment 3)

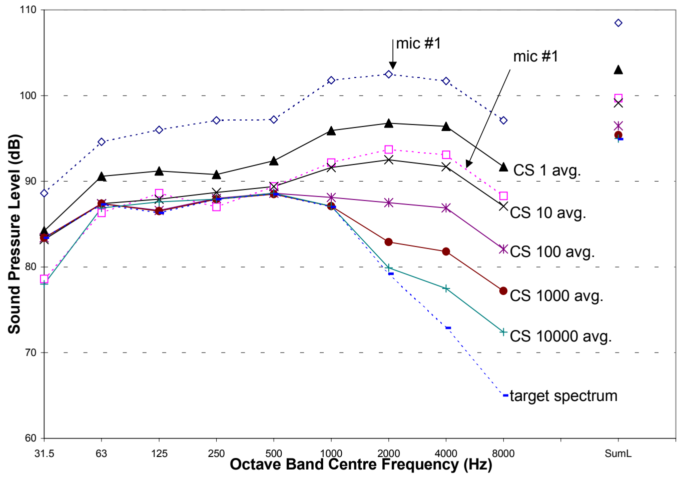

Figure 3 – Cross Amplitude Spectrum for Combined Signals, without Variable Smoothing (experiment 3)

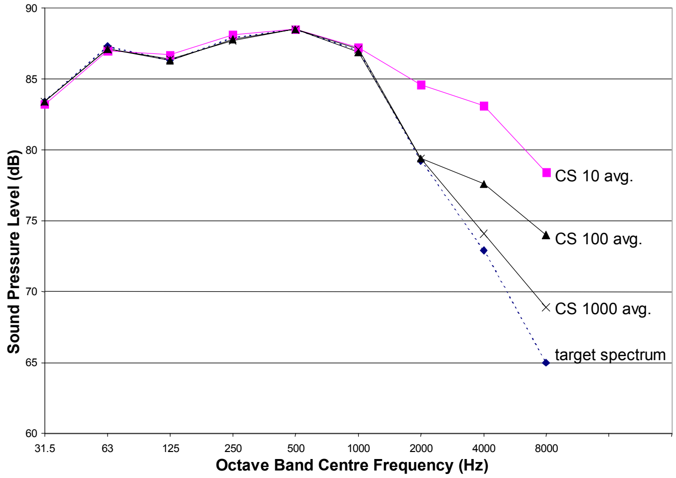

Figure 4 – Cross Amplitude Spectrum for Combined Signals, with Variable Smoothing (experiment 3)

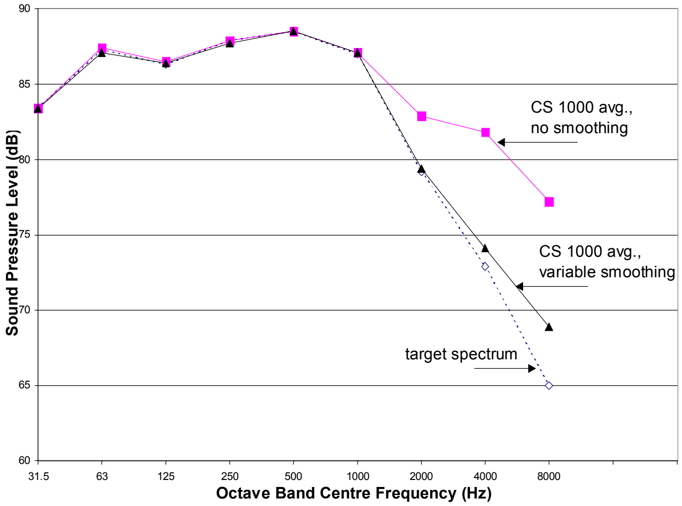

Figure 5 – Comparison between No Smoothing and the Variable Smoothing