Large Signal-to-Noise Technique for Unsteady Pressure Measurements

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IN order to obtain mean and fluctuating pressure measurements, many investigators perform their experiments while operating at the maximum speed of the wind tunnel. Hunt and Fernholz,[1] for example, point out that the speed should be in excess of 10 m/s in order to maximize the pressure signal and to minimize sound pressure contamination. With the I.I.T. Environmental Wind Tunnel, as with many tunnels, this may not be the most efficient operating condition. For example, if the sound level increases with velocity at a power larger than 2, or if the flow conditions in the tunnel are less desirable at high velocities, the operation at a low or moderate freestream speed may be more appropriate. One of the earlier and most valuable discussions of sound contamination in wind tunnels was presented by Batchelor.[2] In wind tunnels that are not carefully designed to eliminate sound contamination, one is either restricted to mean pressure measurements or must accept the additional component in the signal. This contamination is especially critical in wind engineering applications where the frequencies of interest lie in that region where generated noise due to the fan, turbulence manipulators, and the tunnel geometry are most prominent. In these cases, a significant percentage of the unsteady pressure signal being measured will most likely be due to this additional component. Some wind engineers use this as an additional safety factor in predicting unsteady wind loads on buildings and structures. The technique presented here has been successfully used to remove this ever-present undesirable sound contamination from unsteady, low-level pressure signals.

At I.I.T., we often utilize a freestream velocity of 3.8 m/s in the low-speed section of the Environmental Wind Tunnel for studying atmospheric flows around simulated structures and building models. With this comparatively low velocity, the mean and unsteady differential pressures on the model are of the order of 10^{-4} psid. The sound pressure level inside the tunnel is of the same order of magnitude, but because of its frequency content it dominates over the pressure fluctuations occurring on a model placed in the simulated atmospheric surface layer.[3] This sound-saturated pressure signal results in erroneous rms readings which are insensitive to changes in the monitored port, model orientation, or test boundary layer.

The percentage of the sound component present in the signal was determined through the overall rms of the signal and by the peak-to-peak value of its correlation function. A comparison of these for several sound conditions in the tunnel indicated that at least 96% of the sound pressure fluctuations were entering the system through the model ports. Thus, the most any sound insulation of the transducer and tubing could provide would be a 4% reduction. Narrow-band filtering of the sound component is not a satisfactory solution because it would also remove a substantial and relevant part of the pressure signal from the model. Therefore, a subtraction technique was adopted to remove the pressure signal due to the contaminant sound from the output of the transducer.

The subtraction technique involved placing, inside the tunnel, a probe which sensed only the sound pressure fluctuations and provided a proportional electrical signal. The sound signal was subtracted from the sound-saturated pressure signal of the model transducer. A preliminary scheme involving a precision sound level meter revealed the importance of matching the dynamic characteristics of the sound and pressure sensors in the subtraction of undesirable noise.[3] In particular, the main problem with such a system was its inability to match the phase of all frequency components in the sound pressure fluctuations, as sensed by the sound level meter, with those sensed by the building-model pressure transducer. Based on this experience, two identical transducers were used in the final scheme.

To hold the transducer and to channel the sound pressure fluctuations, a special sound pressure probe was built.[3] The sound probe, which utilized a miniature static-pressure probe, was dynamically tuned to match the characteristics of the building-model pressure system. Using sinusoidal pressure fluctuations, the length of the static-pressure probe was adjusted until the natural frequency matched the 230 Hz value of the building-model pressure system. With the required probe length, a dynamic calibration curve[3,4] was generated for frequencies up to 300 Hz. In addition, the frequency-compensated response of the sound probe was obtained using active-filter design parameters identical to those employed in the model pressure system.[3] A comparison of these calibration curves with those of the model system showed them to be nearly identical. By matching the dynamic characteristics of the two systems, one is assured that the amplification and phase shift for each frequency of the signal are identical for both of these second-order-like systems. Thus, all of the frequency components of the sound are always aligned for subtraction.

In order to implement this scheme, the output of the sound probe, proportional to the sound pressure fluctuations in the tunnel, was fed to the analog circuit shown in Fig. 1. There it was subtracted from the amplified output of the building-model pressure transducer in order to obtain a signal proportional only to the instantaneous pressure on the model.

To determine the optimum location of the sound probe, with respect to the building model, a pure-tone tuning scheme was devised. It involved the excitation of the system by sinusoidal pressure fluctuations of various frequencies while monitoring the relative amplitude and phase differences of the transducer signals. The effect of different probe positions on these parameters was monitored in order to find an optimum condition where the signals were equal in amplitude and remained in phase for all frequencies of interest.

An acoustic speaker mounted on a tripod and located in the far-stream portion of the test section was used to supply the pressure fluctuations. It should be pointed out at the start that the location of the speaker had no effect on the tests described in the following. The amplified output of each transducer was monitored on a dual-beam oscilloscope with channels 1 and 2 being displayed in the x and y coordinate directions, respectively. The shape of the resulting Lissajous figures indicated the phase and amplitude differences between the periodic inputs, e.g., see the right portion of Fig. 2.

Using this forced excitation, certain frequencies and probe locations were found to produce large phase and amplitude differences. A comparison of these critical frequencies showed them to coincide with those observed in the sound contaminated pressure signals. The lengths of these sound waves scale with the different dimensions of the closed-return tunnel, e.g., the width and height of the test section and the length of the tunnel circuit and its four legs. Phase differences similar to those depicted in the oscillograms of Fig. 2 were also used in an attempt to identify the character, and possibly the source, of these sound waves. While the wave structure is very complex, the observations seemed to suggest standing waves which may or may not be traveling around the tunnel.

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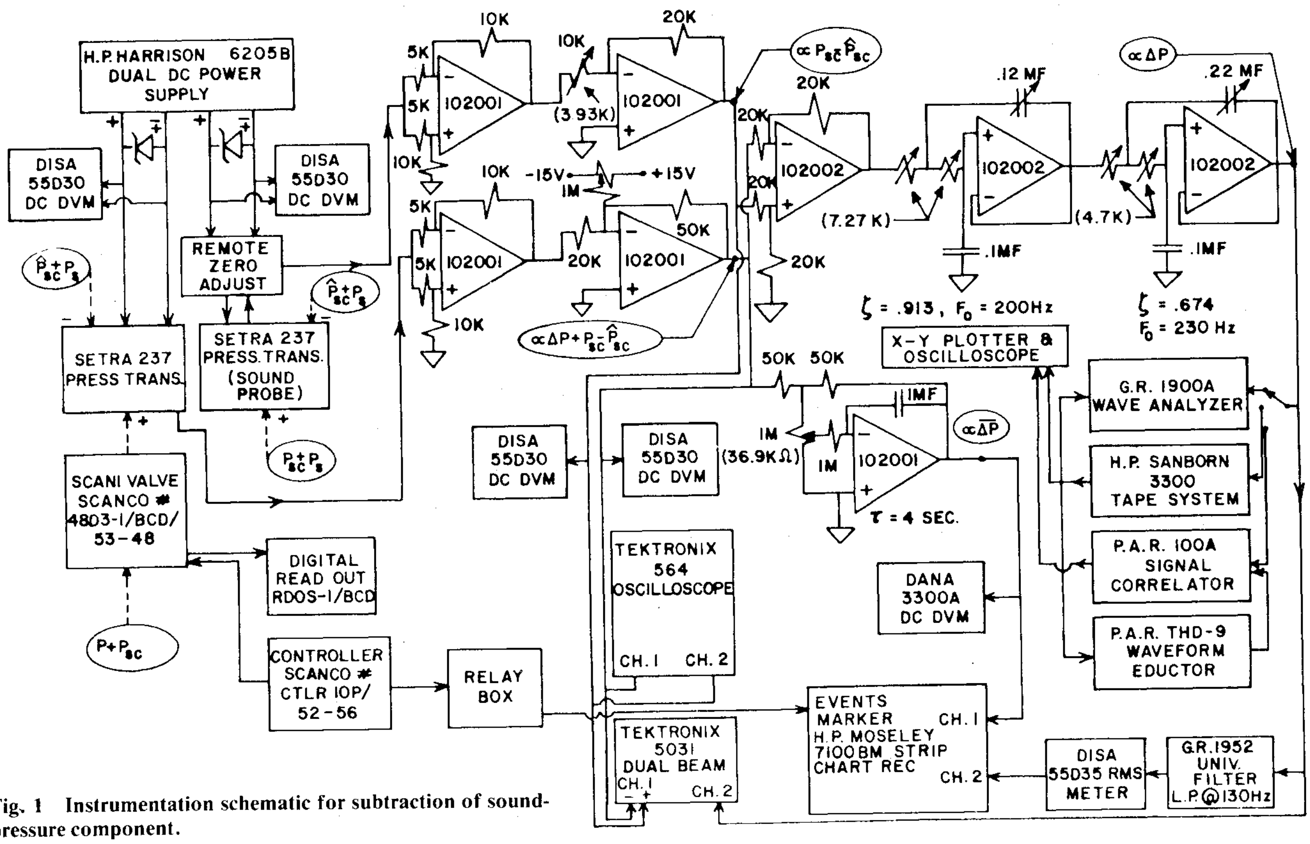
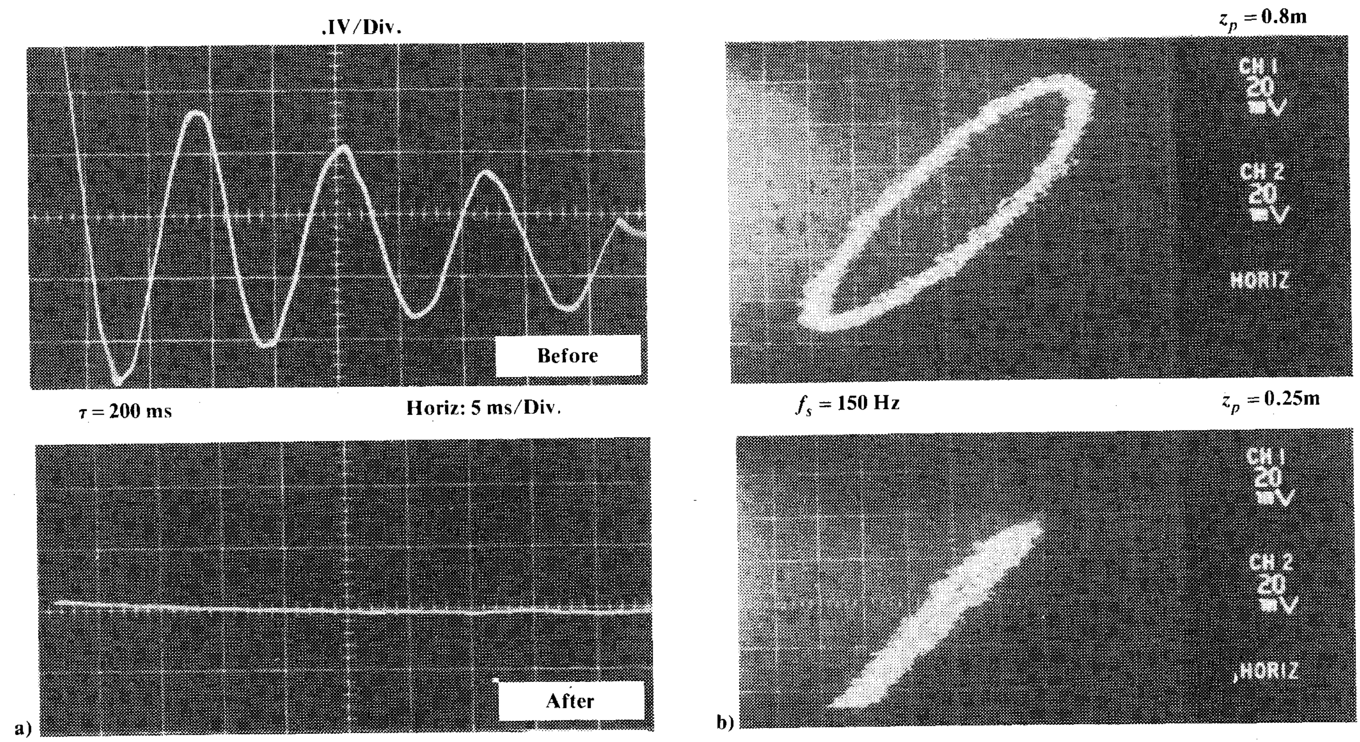


Fig. 1 Instrumentation schematic for subtraction of sound-pressure component.



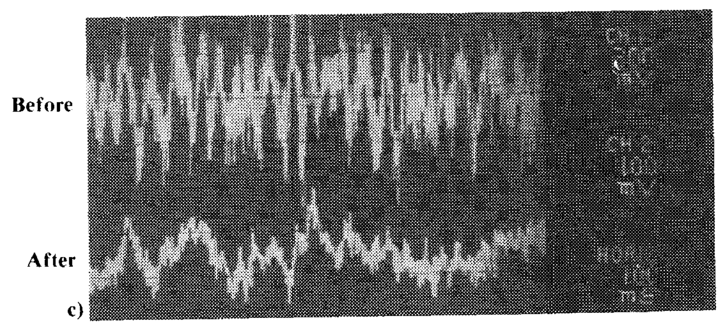


Fig. 2 Oscillograms showing a) autocorrelation functions of model output before and after sound subtraction, b) Lissajous figures used to obtain phase and amplitude relations, and c) typical signals before and after sound subtraction.

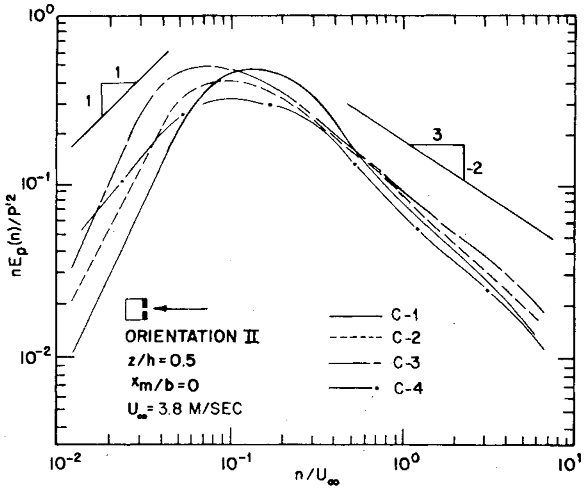


Fig. 3 Normalized spectra of pressure fluctuations on upstream face of building at half the building height.

Such waves could possibly be excited by the fan or the various turbulence manipulators. Batchelor reported[2] on similar waves in one of his experiments with wind tunnels. Therefore, for the signals to be in phase for all sound frequencies present in the tunnel the sound probe must be near the model of the building being tested in the simulated layer.

Based on these findings, the sound probe was mounted in the sidewall of the test section, close to the tunnel floor, (see Fig. 3 of Ref. 4). Because of the size of the sensing region of the probe, and its location upstream of the model, no detectable influence of the static pressure fluctuations in the boundary layer on the sound signal was found to occur within the frequencies of interest.[3]

The final tuning of the subtraction system was done while the tunnel was operating under the model testing conditions. This involved the fine matching of the signal amplitudes, by adjusting the gain of the amplifier in the sound probe leg of the subtraction circuit, Fig. 1, in order to make the rms of the subtracted output a minimum. This optimum setting was found to be the same for all test conditions.

In some cases, the tuned subtraction system provided a total reduction in the rms of the model pressures of as much as 80%. The left portion of Fig. 2 displays the autocorrelated outputs of the low-frequency portion of the nonsubtracted and the sound-subtracted output from the building model. Before the sound subtraction, well-defined frequencies corresponding to the sound contamination in the signal are noted. With the aid of the sound-subtraction scheme, however, Fig. 2 reveals the removal of the sound pressure contaminant. Oscilloscope traces of the nonsubtracted and subtracted model outputs while operating under a testing condition are shown in the bottom part of Fig. 2. In order to compare these signals one should note that because of the oscilloscope scale setting, the amplitude of the nonsubtracted output of the building model is actually twice as large as displayed. Figure 2 indicates how well the subtraction system performs in removing the sound pressure contamination from the signal. This technique therefore provides us with a signal from which we can make accurate and reliable fluctuating pressure measurements on building models. An example of the type of unsteady pressure measurements made possible by this technique is shown in Fig. 3.

Acknowledgment

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References

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Bessel Function Evaluation of the Clamped End Bending Moment of an Impulsively Loaded Beam

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IN a recent Note by Sagartz and Forrestal,[1] dealing with stresses in an impulsively loaded, semi-infinite beam, the following expression was obtained for the bending moment at the clamped end:

$$\frac{M}{Lrc_b}=\frac{2\alpha}{\pi}\int_0^\alpha \frac{(\alpha^2-\rho^2)^{1/2}\sin\rho_\tau}{[\alpha^2-(1-\gamma)\rho^2]\rho}\,d\rho \tag{1}$$

(for the significance of the various parameters, see Ref. 1.) In the present Note, we show that Eq. (1) can be given in terms of Bessel functions and Bessel function integrals.

The change of variable, $\rho=\alpha\cos\theta$, reduces Eq. (1) to the following

$$\frac{M}{Lrc_b}=\frac{2}{\pi}\int_0^{\pi/2}\frac{\sin(z\cos\theta)\sin^2\theta}{\cos\theta[1-(1-\gamma)\cos^2\theta]}\,d\theta$$

$$=y_1(z)-\gamma y_2(z) \tag{2}$$

where $z=\alpha\tau$, and

$$y_1(z)=\frac{2}{\pi}\int_0^{\pi/2}\frac{\sin(z\cos\theta)}{\cos\theta}\,d\theta \tag{3a}$$

$$y_2(z)=\frac{2}{\pi}\int_0^{\pi/2}\frac{\sin(z\cos\theta)\cos\theta}{1-(1-\gamma)\cos^2\theta}\,d\theta \tag{3b}$$

By differentiation

$$\frac{dy_1}{dz}=J_0(z) \tag{4}$$

$$(1-\gamma)\frac{d^2y_2}{dz^2}+y_2=J_1(z) \tag{5}$$

where use has been made of the following integral representations for the Bessel functions $J_0(z)$ and $J_1(z)$ (Ref. 2):

$$J_0(z)=\frac{2}{\pi}\int_0^{\pi/2}\cos(z\cos\theta)\,d\theta$$

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