Optical Crossed-Beam Measurements of Turbulence Intensities in a Subsonic Jet Shear Layer

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Theme

An analytical relationship is developed between the probability density of flow velocity fluctuations and the cross-correlation of two radiation sensor outputs. The location of the measurement is chosen by triangulation between two lines of sight, which pass through the jet plume. Experimental results obtained by this technique for turbulent intensity measurements in the shear layer of a cold subsonic air jet are present.

Content

This paper presents an analytical extension of the crossed-beam technique,[1-3] which allows the turbulence level in the jet flowfield to be measured by the remote optical technique. Denote the time series of signals from the two photometers by i_A and i_B, respectively (Fig. 1).

It can be shown that the probability density of the flow speed fluctuations $P(U)$ can be approximated by the measurable cross-correlation of the time derivatives of i_A and i_B, $R_{AB}^{(2)}(\xi,\tau)$, as expressed by the following equation:

$$P(U) = \frac{\xi}{\tau} = \tau R_{AB}^{(2)}(\xi,\tau)/\xi \int_{-\infty}^{\infty} \frac{1}{\tau'} R_{AB}^{(2)}(\xi,\tau')d\tau' \quad (1)$$

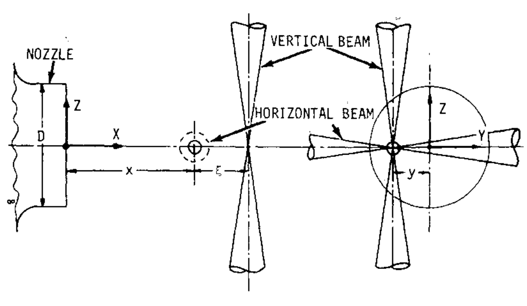

Fig. 1 Coordinate system.

where

$$R_{AB}^{(2)}(\xi,\tau) = \frac{1}{T}\int_0^T \frac{\partial i_A(t)}{\partial t}\frac{\partial i_B(\xi,t+\tau)}{\partial t}dt \quad (2)$$

where ξ is the normal distance between two light beams and τ is the time delay between two signals. One main assumption underlying the aforementioned derivation is that the temporal microscale of optical inhomogeneities should be much smaller than the half width of the probability density of the transit times between two light beams. For statistical stationary processes, Eq. (2) is equivalent to

$$R_{AB}^{(2)}(\xi,\tau) = (\partial^2/\partial\tau^2)R_{AB}(\xi,\tau) \quad (3)$$

$$R_{AB}(\xi,\tau) = \frac{1}{T}\int_0^T i_A(t)i_B(\xi,t+\tau)dt \quad (4)$$

Denote the Fourier integral transforms of these two expressions by $S_{AB}^{(2)}(\xi,f)$ and $S_{AB}(\xi,f)$, respectively. Then Eq. (3) can be written as

$$S_{AB}^{(2)}(\xi,f) = f^2 S_{AB}(\xi,f) \quad (5)$$

Or, in terms of gain spectrum defined by

$$G_{AB}(\xi,f) = [S_{AB}(\xi,f)S_{AB}^*(\xi,f)]^{1/2} \quad (6)$$

where the asterisk denotes the complex conjugate, Eq. (6) can be rewritten as

$$G_{AB}^{(2)}(\xi,f) = f^2 G_{AB}(\xi,\tau) \quad (7)$$

This states that the gain spectrum from the time derivatives of the sensor outputs is equal to that from the outputs themselves multiplied by the square of frequency.

The crossed-beam measurement was taken on an air jet with diameter $D = 1$ in., which was operated at a speed of 688

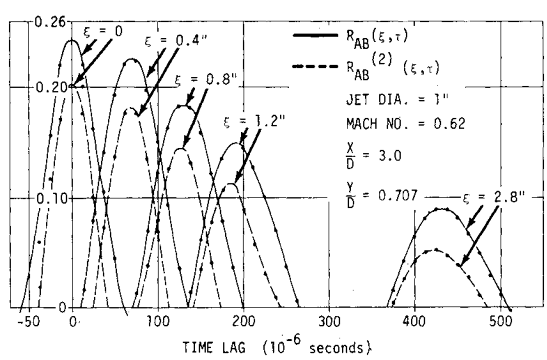

Fig. 2 Cross-correlation functions of signal fluctuations and their second derivatives.

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Index categories: Jets, Wakes, and Viscid-Inviscid Flow Interactions; Nonsteady Aerodynamics; Boundary Layers and Convective Heat Transfer-Turbulent.

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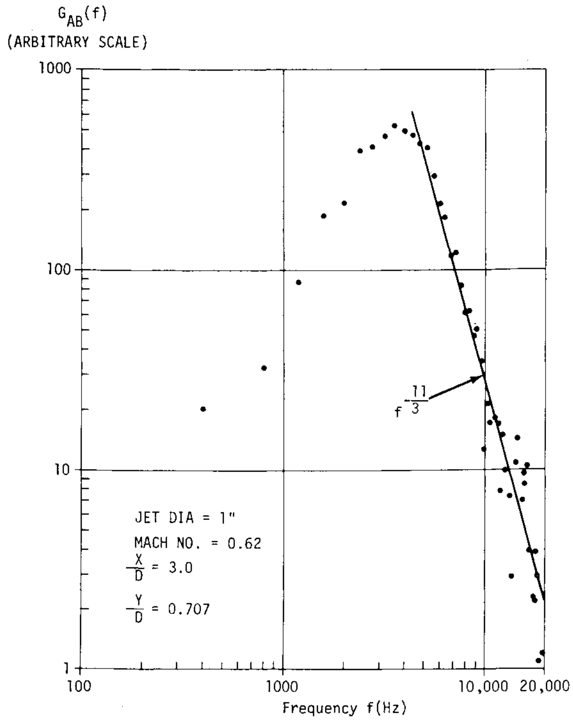

Fig. 3 Gain spectrum of the cross-beam measurement with intersecting beams.

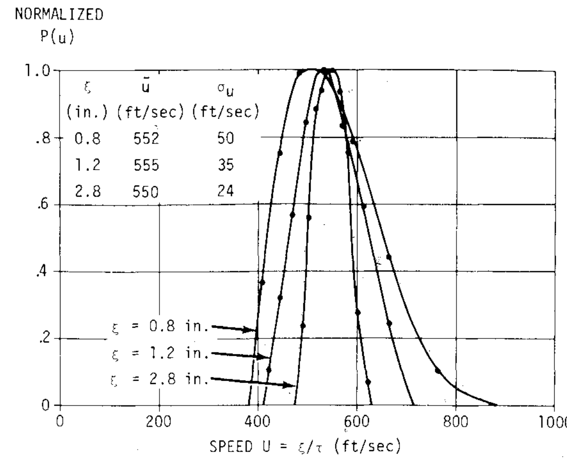

Fig. 4 Normalized probability density of jet speed fluctuations.

fps. The location of the beam crossing in the jet was $X/D = 3.0$ and $Y/D = 0.707$ with $\xi = 0, 0.4, 0.8, 1.2$, and 2.0 in., respectively.

Figure 2 shows the correlation functions for various ξ's up to their first zero crossings on both sides of their peaks. The actual correlation curves were computed over a much wider range of time delays and then shifted until the area under the entire correlation curve became zero. This area shift acts as a filter against large scale signal components.

Figure 3 shows the gain spectrum for $\xi = 1.2$ in. Apparently the high-frequency range of the spectrum follows very closely $-\frac{11}{3}$ power law. This is an experimental verification for the analytical prediction that the crossed-beam correlation is a point-area correction instead of two-points correlation.

Figure 4 shows the probability density of jet speed fluctuations with $\xi = 0.8$ in., 1.2 in., and 2.8 in. The mean convection speeds from these three probability densities are found to be 552 fps, 555 fps, and 550 fps, respectively. The corresponding standard deviations of the convection speed are 50 fps, 35 fps, and 24 fps, respectively, which correspond to turbulence levels of 9.1%, 6.4%, and 4.4%. This figure thus shows how the probability density curves become narrower as the beam separation ξ become larger. This may be partially explained by the increase in the range of transit time variations with beam separation relative to the resolvable transit time interval.

A complete experimental proof of the optical approximation of local probability density fluctuations requires that the experimental results from several beam separations collapse on the same curve. Figure 4 does not show such a collapsing of results. However, such result could also not be expected in view of the intolerable large transit time interval. A better approximation, i.e., a better resolution of transit times, could be anticipated by increasing the beam separation. However, the beam separation cannot be increased much beyond the eddy decay length. A beam separation equal to the eddy decay length ($\xi = 2.8$ in. in this case) gives too small a turbulence level. Apparently eddies with large transit time variations die most quickly during transmit and may not reach the downstream beam. The probability density curve that was derived from $\xi = 1.2$ in. is thus probably the best approximation of the actual probability density of the longitudinal velocity fluctuations.

This discussion shows some practical limitation for the remote detection of turbulence parameters by the crossed-beam technique in flowfields with extreme shear. More sophisticated processing techniques which more accurately prewhitten the common signal components will certainly help, but may not overcome the rapid decay of the correlatable information. Previously, measurements in atmospheric turbulence of moderate shear[3] showed a good radiometric approximation of directly measured velocity distribution functions.

References

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