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Hot Wire Measurement of Velocity Gradients in a Fluid Flow

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Theme

THIS paper presents the results of an experimental investigation of a technique to directly measure the first and second spatial velocity derivatives in a fluid flow. The technique's utility lies in the fact that it does not depend on graphical differentiation or computer curve fitting methods as do the usual techniques for obtaining spatial velocity derivatives. The techniques utilizes an oscillating hot wire anemometer probe traversing the flow in a direction perpendicular to the mean flow. The response signal is processed first through an electronic linearizer and then through a lock-in amplifier. The spatial derivatives are contained in the coefficients of the first and second harmonics of the wire response signal from the lock-in amplifier which is tuned to the frequency of the oscillating probe. The investigation compares the experimental results with graphical and computer derived profiles with a favorable result. A check is also performed to confirm the range of independence of the results from changes in the parameters τ, ω, and R; the lock-in amplifier time constant, the frequency of oscillation, and the amplitude of oscillation.

Contents

A previous study by Kirchhoff and Voci,[1] utilizing a similar technique, determined the applicability of directly measuring the first spatial velocity derivative in the wake of a wedge. This technique was expanded and refined to directly measure the first and second spatial velocity derivatives.

A two-dimensional Taylor series and binomial series expansion of the linearized response provides the basis for the technique.[2] The spatial derivatives are contained in the coefficient of the first and second harmonics of the linearized probe response which can be separated by a lock-in amplifier tuned to the forced frequency of oscillation of the probe.

For the case of one-dimensional flow investigated in this experiment, the oscillating prove linearized voltage response may be expressed as

$$E_L = B\Delta T(U(y_o) + R\ U^1(y_0)\sin\omega t) - R^2/4\cos(2\omega t)$$
$$[-\omega^2 + U(y_o)U^{11}(y_o) + (U^1(y_o))] \qquad (1)$$

where $B\Delta T$ is the calibration constant, R is the amplitude of oscillation, and ω is the forced frequency of oscillation. The T indicates temperature and ΔT indicates sensor temperature minus fluid temperature.

The lock-in amplifier basically tunes into the coefficient of the ω term by the reference signal of the oscillating frequency of the probe which is fed into the lock-in amplifier. The lock-in amplifier has the capability of doubling the reference signal frequency to isolate the 2ω term also.

The rms amplitude of the coefficients were measured by the lock-in amplifier. Turbulent fluctuations were averaged out via the averaging technique the lock-in amplifier employs to give the output signal a narrow bandwidth characteristic around either ω or 2ω depending on which coefficient is desired.

The wake of a flat plate in a low-speed ($U_\infty = 16$ fps) tunnel provided the flowfield to test the technique. Flow traverses were made across the wake at a point 1/2 in. downstream of the plate. The maximum turbulence level in the flow at this plane of traverse was 10%. This turbulence level is directly proportional to the time τ necessary to average the noise in the lock-in detection process.

The ability to measure the second derivative term depends on the signal to noise ratio of the linearized voltage response of the anemometer. This is in turn affected by the turbulent fluctuations which show up as signal noise, and the combination of ω^2, $U(y_o)U^{11}(y_o)$, and $[U^1(y_o)]^2$, which determine the magnitude of the cos $(2\omega t)$ coefficient. It is evident that the applicability of this technique depends on the magnitude of the above values.

Figure 1 illustrates the results of the investigation. The top curve is the output of a linearizer and represents the velocity U as a function of position y in the wake. The next two curves are the output of the lock-in amplifier which is extracted from the fluctuating probe response at ω and 2ω. The middle curve represents $U^1 = dU/dy$ vs y and the bottom curve is proportional to $U^{11} = d^2U/dy^2$ vs y. It can be seen from Eq. (1) that the probe motion influences the response at 2ω. Visual differentiation of the velocity curve confirms the shape of the U^1 and U^{11} curves.

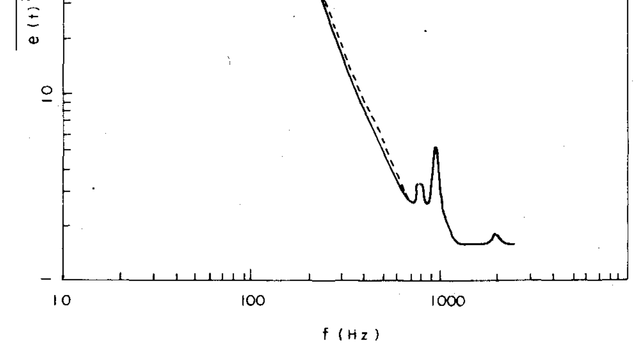

Fig. 1 Lock-in amplifier output as a function of frequency of oscillation (ω) of hot wire at $(du/dy)_{max}$.

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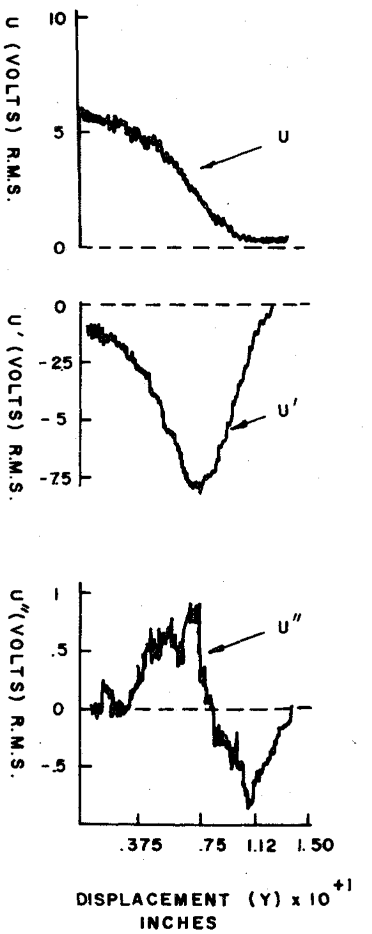

Fig. 2 Lock-in amplifier output vs displacement for U, U', and U''.

Figure 2 is a spectral analysis of the probe linearized response when the probe was located at the point of maximum $\mathrm{d}U/\mathrm{d}y$ in Fig. 1. When the probe was oscillating at 55 Hz, the strong signal in the spectrum is clearly seen above the background turbulence; a similar result was observed when the probe was oscillating at 200 Hz. No signal in the spectrum was observed at twice the frequency of probe oscillation because the dominant term in Eq. (1), $\mathrm{d}^2U/\mathrm{d}y^2$, was zero at this point in the flow. The peak in the spectrum at 140 Hz is present both with and without oscillations of the probe indicating that it is due to the flow as explained in Ref. 4. The natural or resonance frequency of the wire was calculated to be 980 Hz and a strong signal is also observed on Fig. 2 around 1000 Hz. The excitation response of the wire at 980 Hz was several orders of magnitude below the response due to the resonating of the wire at the 55 Hz oscillation frequency of the probe.

References 3 and 4 contain the complete parametric investigation of the dependence of U^1 and U^{11} on R,ω, and τ. Graphical and computer curve fitting determinations of U^1 agreed with the experimental results to within 12%. A graphical comparison of the calculated U^{11} and experimental results also exhibited favorable results.

References

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[2] Kirchhoff, R. H. and Burbank, R. A., "The Response of a Hot Wire Oscillating in a Shear Flow," *AIAA Journal*, Vol. 12, Jan. 1974, pp. 96-98.

[3] Barnoski, J. J., "Hot Wire Measurement of Velocity Gradients in a Fluid Flow," AIAA Paper 73-50, Washington, D.C., 1973.

[4] Barnoski, J. J., "Hot Wire Measurement of Velocity Gradients in a Fluid Flow," M.S. thesis, Sept. 1972, Dept. of Mechanical Engineering, University of Massachusetts, Amherst, Mass., 1972.