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THE RESOLUTION OF COHERENT STRUCTURES BY DYNAMIC SCHLIEREN

M.R. DAVIS

Department of Civil and Mechanical Engineering
University of Tasmania
GPO Box 252C, Hobart, Tasmania 7001
AUSTRALIA

ABSTRACT

The response of the dynamic, slab schlieren system is analysed and its enhanced responsiveness to vortex structures is thus demonstrated. Observations show evidence of vortex structures in natural jet mixing only close to the nozzle, whilst the application of pure tone excitation produces a concentration of energy into subharmonic components. The reductions in random mixing due to excitation exceeded the overall added strength of excited components in the observations to produce moderate overall reductions in observed signals under excitation.

1. INTRODUCTION

Identification of regular disturbances in turbulent shear flows generally relies upon some form of conditional sampling combined with signal or record averaging in order to elucidate the character of the regular components. Whether the conditional sampling is based upon selective extraction of photographic images on a subjective basis, or upon a more specific turbulence signal criterion, the influence of the conditional procedure upon the result obtained is not always clear and in particular the contribution of the component identified to the total motion is not always evident.

In the present paper a particular form of the dynamic schlieren system is considered for which the system physical geometry confers upon the detected signal an enhanced sensitivity to coherent structures in the flow. By this means it is possible to detect coherent structures without conditional sampling on a quantitative basis under conditions where point detection systems would require multi-point conditional sampling to resolve large-scale coherent disturbances. Apart from the advantage of avoiding the application of selective conditional sampling criteria, this approach also has the advantage of allowing direct estimation of the total energy of coherent components in relation to turbulent components of the mixing flow, and it is this latter aspect which will be considered here.

2. SENSING SYSTEM RESPONSE

a. Response to toroidal vortices

The modified schlieren system has been described by Davis (1987), and consists of a conventional schlieren visualisation system in which a circular parallel illuminating beam is formed by a steady, rectangular light source and a spherical mirror (152 cm focal length). A mask is placed across the beam before it passes through the flow so that only a slab beam reaches the flow as shown in Figure 1. This slab beam is focused in the conventional way onto a knife edge, and a photodiode is placed immediately beyond the knife edge so as to detect the entire illumination power that passes the knife edge. If the steady source of illumination is rectangular and uniform, and if the knife edge is oriented so as to detect axial beam deflexions (x direction), then the scaled unsteady output from the photodiode (S(t)) is given by

$$S(t) = \int_{x_1}^{x_2} \int_{flow} \frac{\partial \rho}{\partial x} \, d\,A\,dx \qquad (1)$$

where the density gradient $\frac{\partial \rho}{\partial x}$ is in the axial direction and the integration is over the complete flow cross sectional area (A) between the upstream and downstream faces of the detection slab ($x_1 < x < x_2$).

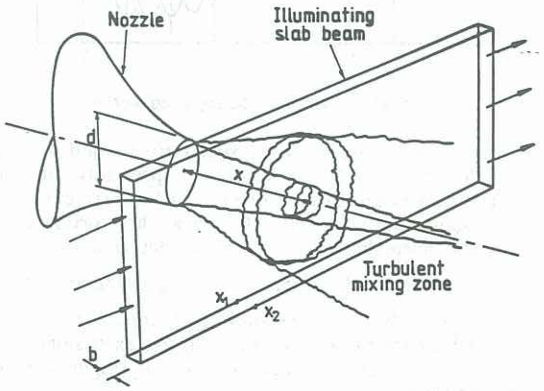

Figure 1. General arrangement of sensing system

If the coherent structures present in the initial region of an axisymetric jet are in the form of toroidal ring vortices, then an approximate representation of the response of the slab sensing system can be based on the two dimensional distribution of density perturbation (ρ) about the vortex axis provided that the core radius (r_c) of the vortex is much less than the radius of the torus (R):

$$\rho/\rho_c = (1 - r^2/2r_c^2) \qquad \text{for } r < r_c \qquad (2)$$

and $$\rho/\rho_c = r_c^2/2r^2 \text{ for } r > r_c \qquad (3)$$

It then follows that the output signal from the detection system is given by

$$\bar{S}_v(\bar{t}) = S_v(\bar{t})/4\pi\, r_c\, \rho_c\, R = (F(\bar{t}_1) - F(\bar{t}_2)) \qquad (4)$$

where $\bar{t}_i = (x_i - U_c t)/r_c$, V_c = convection velocity of the vortex, t = time (zero when vortex is at $x = (x_1 + x_2)/2$)

$$\text{and} \quad F(\bar{t}) = \pi/4\bar{t} \qquad \text{if } \bar{t} > 1 \qquad (5)$$

$$\text{or} \quad F(\bar{t}) = \left(\tfrac{5}{6} - \tfrac{1}{3}\bar{t}^{\,2}\right)\, 1 - \bar{t}^{\,2} + (\pi/2 - \mathrm{Tan}^{-1}(\bar{t}^{\,2} - 1)^{1/2})/2\ |\bar{t}| \qquad (6)$$

if $\bar{t}<1$. Figure 2 illustrates the system response to a single vortex for varying detection beam thicknesses ($b = x_2 - x_1$). In all cases the response is an odd function of time, and as the beam thickness increases the responses take on the form of relatively isolated positive and negative excursions as the vortex passes into and out of the slab beam. Figure 3 shows the signal energy which results from a single vortex passing the slab beam, in terms of the normalised output function $\bar{E}^2_v$,

$$\bar{E}^2_v = \left(\frac{1}{4\pi\, r_c\, \rho_c\, R}\right)^2 \int_{-\infty}^{\infty} S^2(\bar{t})\, d\bar{t} \qquad (7)$$

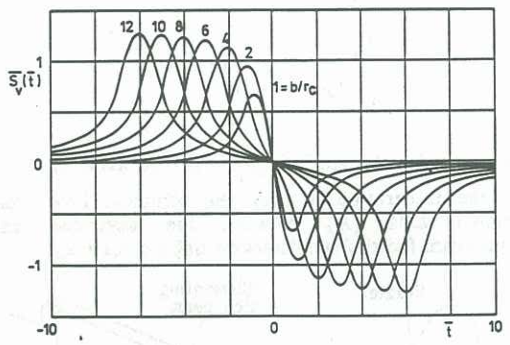

Figure 2. System response to isolated vortex

The intensity of the detected signal rises rapidly with beam thickness until the beam is appreciably thicker than the core radius of the vortex. For beam thicknesses larger than approximately 10 times the vortex core radius the normalised energy of the detected signal is almost constant with $\bar{E}^2_v$ then being approximately 6.0. This corresponds to the response in figure 2 having two fairly well separated positive and negative excursions and leads to the signal energy due to a single vortex becoming then

$$\int S_v^2\,(t)\, dt \simeq (6\, r_c/V_c)\, (4\pi\, \rho_c\, r_c R)^2 \qquad (8)$$

b. Response to small scale random structures

The system response to small scale structures is most easily specified in terms of the integral scales of turbulent fluctuations, as has been described by Winarto and Davis (1984) for the crossed pencil beam arrangement. If the upstream and downstream faces of the detecting slab beam are sufficiently widely spaced

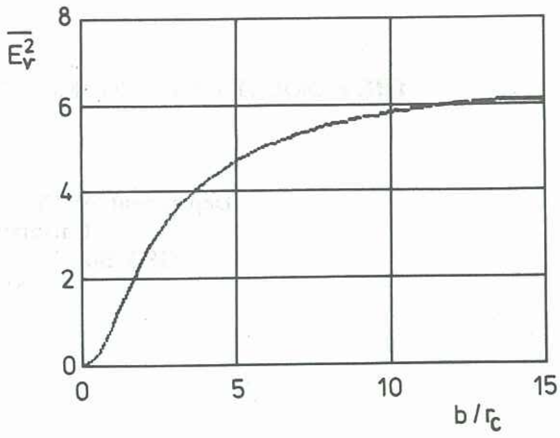

Figure 3. Signal energy due to single vortex

(Davis, 1982) that the fluctuations on the two beam faces are effectively uncorrelated, and also if the average properties at the two beam faces are assumed to be the same (i.e. the flow does not show strong streamwise changes over the distance $x_2 - x_1$), then we may put the output signal intensity as

$$\overline{S_r^2(t)} = 2\iint_{\text{flow}} \overline{\rho(\tilde{r}_1)\ \rho(\tilde{r}_2)}\, d\, A_1\, d\, A_2 \qquad (9)$$

where $\tilde{r}$ denotes the position vector in the cross sectional plane of area A. Winarto and Davis (1984) showed that in mixing jet flows there was not a significant directional variation of relevant turbulent properties in the cross sectional plane, and it follows that we may define the integral scale for present purposes as

$$l = \int \frac{\overline{\rho(\tilde{r}_1)\ \rho(\tilde{r}_2)}}{\overline{\rho^2(\tilde{r}_1)}}\, d\,(\tilde{r}_2 - \tilde{r}_1)$$

$$= \int R_{1\,2}\,(\tilde{r}_2 - \tilde{r}_1)\ d(\tilde{r}_2 - \tilde{r}_1) \qquad (10)$$

Thus the detected signal intensity is

$$\overline{S_r^2(t)} = 2\int \overline{\rho^2(\tilde{r})}\ l^2(\tilde{r})\, dA \qquad (11)$$

In the turbulent annular initial region of a circular jet the distribution of turbulent fluctuations peaks within the annular shear layer, and both thickness of the shear layer and integral scale increase with streamwise distance from the nozzle. Thus if $\overline{\rho^2_m}$ denotes the maximum density fluctuation intensity at the shear layer centre we may use the data of Winarto and Davis (1984) to put for the annular region

$$S_r^2(t) = 0.018\, \overline{\rho_m^2}\, x^2 d^2 \qquad (12)$$

where d is the jet nozzle diameter.

c. Relative response to vortices and random mixing

From the results of equations (8) and (12) we see that the ratio of vortex contributions to that of random mixing contributions to the total observed signal is

$$\frac{\overline{S_v^2}\,(t)}{\overline{S_r^2}\,(t)} = 1.31 \times 10^4 \left(\frac{\rho_c}{\rho_m}\right)^2 St_v \left(\frac{r_c^3}{x^2 d}\right) \qquad (13)$$

where St_v = Strouhal number (fd/U_v) of vortices passing at velocity U_v and frequency f. For the tests to be described cross correlation measurements between the slab beam and a displaced microphone indicate U_v = 0.8 U_j approximately, and the dominant response was at St_v = 0.7. Whilst it is difficult to estimate the core radius r_c of vortex structures, Davis (1987) carried out tests using a shock tube to generate discrete vortices in the induced flow from a nozzle, and from the slab beam signal character concluded that $r_c = d/6$ at least at x/d = 3. Therefore if the density variations in the core of regular disturbances (ρ_c) and in turbulent mixing (ρ_m) are of comparable magnitude, we see that the ratio $\overline{S_v^2}(t)/S_c^2(t)$ will have a value of 4.7. These figures show that the vortex signals are expected to be approximately 7dB greater than the random turbulent signals and demonstrate clearly the capability of the slab beam system of enhancing regular structure components in its output so that conditional signal analysis is not required.

3. OBSERVATIONS OF NATURAL AND EXCITED FLOWS

Observations to be described were made in the mixing flow from a 12 mm circular nozzle discharging at a Mach number of 0.7 into the laboratory. The slab schlieren beam was set up to have a beam thickness b/x = 1/8, this being sufficient to ensure that fluctuations on upstream and downstream forces of the beam were not significantly correlated (as demonstrated by Davis, 1982). A near field microphone was positioned just outside the turbulent shear layer, and figure 4 shows the phase spectrum between the microphone and the slab schlieren signal. It is seen that close to the nozzle exit the phase spectrum for Strouhal numbers greater than 0.5 has a value close to $\pi/2$. This is indicative of vortex like structures in the shear layer, since the schlieren response to a passing vortex (figure 2) is an odd function of time whilst the microphone pressure response to a vortex is an even function of time. However for x/D = 3 and beyond this clear evidence of ring vortex structures is no longer evident, the microphone and schlieren signals then being in phase for higher Strouhal numbers. The increase of phase angle at low Strouhal numbers which is a characteristic feature of these phase spectra indicates a delay in the correlated pressure signal which appears to be caused by the schlieren system detecting flow structures which develop as they move downstream and radiate strong pressure disturbances back to the sensing microphone with phase lag.

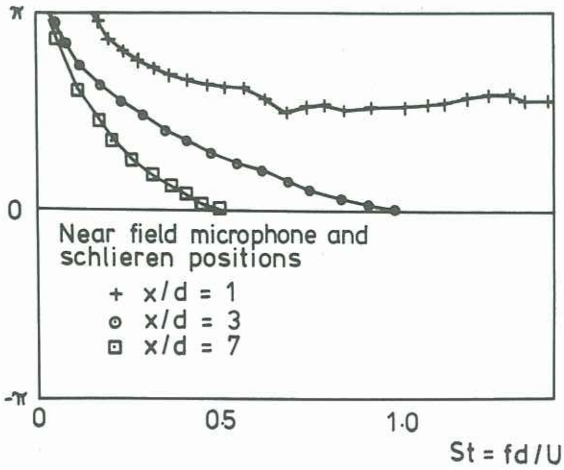

Figure 4. Phase spectra with near field microphone in natural jet.

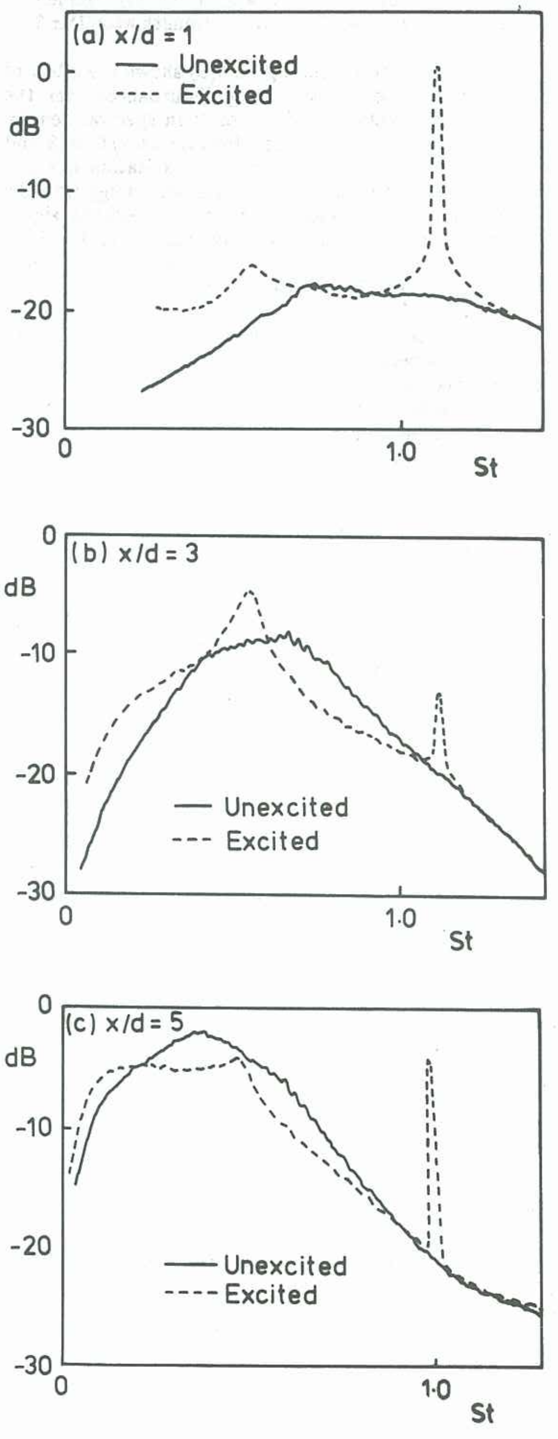

Figure 5. Comparative signal spectra in natural (solid line) and excited (dashed line) cases.

The nozzle was excited with a pure acoustic tone generated by a horn located in the upstream settling chamber and facing directly downstream at a Strouhal number of 1.12. Comparative spectra with and without this excitation obtained from the schlieren system are shown in figures 5(a) – (c). The results show clear evidence of vortex pairing through the progressive strengthening of subharmonic components at St = 0.56 and 0.27 with downstream distance from the nozzle. However, it is clear that the lower of the Strouhal number components only develop strongly at or beyond the end of the initial region of the jet (x/d>5) where the flow is fully turbulent over the cross section, and this second subharmonic is not nearly as clearly defined as the first which reaches its greatest strength at x/D ≃ 3.

Close to the nozzle, figure 5(a) shows the effect of excitation to superimpose strong disturbances over the natural jet fluctuations and increases in spectral density occur at all Strouhal numbers. However at x/D = 3 and 5 we can see clear evidence that the excitation has had the effect of concentrating the fluctuation energy into the excited components, and reductions of detected signal energy of up to 5 dB approximately occur at x/D = 3, St = 0.75 when the excitation is applied. This effect weakens at x/D = 5, and the relatively broad nature of the second subharmonic component at that position prevents a similar effect being identified at lower Strouhal numbers. The excitation applied in these tests corresponded to a velocity fluctuation at the nozzle exit plane of 0.56% of the jet exit velocity and has given rise to a first subharmonic component at x/D = 3 which is stronger than the natural jet fluctuations at its peak by 5.5 dB. This result is in generally good agreement with the expectation resulting from equation 13 that regular vortex structures would appear more strongly in the slab beam signal by about 7 dB.

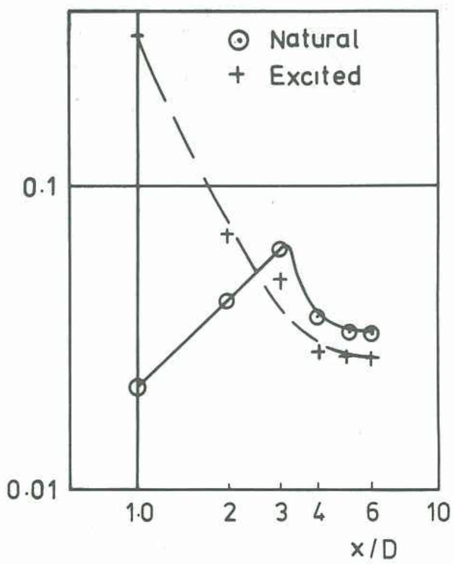

Figure 6. Total signal intensity (ordinate shows radians, total r.m.s. beam deflection)

The total signal intensity is shown in figure 6. Close to the nozzle the excitation is strong and increases total observed mixing intensity. In this region the signal under natural mixing increases with x^2 as expected from equation 12. Beyond x/D = 3, the application of excitation produce a slight reduction of total mixing intensity, and it appears here that reductions in random mixing caused by excitation exceed the overall strength of excited regular components.

4. CONCLUSIONS

It has been demonstrated that the slab beam geometry of the dynamic, quantitative schlieren system gives rise to an enhanced responsiveness to regular vortex structures. Under natural, unexcited mixing conditions, the phase spectra with near field microphone signals show evidence of vortex like structures only close to the nozzle, whilst beyond x/D = 3 the phase spectra reflect the radiation of pressure disturbances from structures which develop in strength as they move downstream of the observation point. Under pure tone excitation, clear evidence of development of subharmonics is found, and spectra show that excitation can concentrate mixing energy into more confined frequency ranges. There is also evidence that excitation can reduce total turbulent mixing intensities.

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