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Acoustic Coupling in a Turbulent Flow

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1 INTRODUCTION

Recent studies of some of the "simpler" turbulent flows have established the presence and importance of large coherent structures (the large eddy) - see, for example Crow & Champagne (1971), Brown & Roshko (1974), Lau & Fisher (1975). Experimental studies of jet and mixing-layer flows have, in the main, been confined to visualisation and the evaluation of statistical properties of the flow. However, it is now apparent that a departure from the classical statistical treatment and modelling is not only warranted, but necessary if the basic mechanisms of the flow are to be examined: the properties and characteristics of the large coherent structure prove surprisingly elusive to measurement by the traditional means.

From the early stages of this work it was recognised that the large structure suffers an inherent uncertainty in scale and spacing, with consequent poor definition in spectral or correlation data. Much of the information obtained from the passage of a single coherent eddy past a laboratory probe is lost when averaged with data generated by similar structures of slightly different scale and frequency of occurrence.

The work presented here is an early account of the development of measurement methods and approaches and some simple properties deduced from the application of these methods. Using new sampling approaches, it is shown that the large-scale features of a turbulent, near two-dimensional jet flow may be measured and described on a deterministic rather than a stochastic basis.

2 FLOW APPARATUS

The apparatus used to generate the jet flow consists essentially of a large compressed air vessel blowing down through a choked valve to a cylindrical muffler, followed by a contraction to the 1cm x 5cm jet nozzle. Screens are used to reduce the turbulence level of the contracting stream and for the acoustic-coupling experiments it was necessary to line the muffler with acoustic-absorbing material to prevent the occurrence of standing waves at discrete resonant frequencies.

3 ACOUSTIC COUPLING OF THE FLOW

Initial experiments aimed at reducing the uncertainty in wavelength of the large structures in the jet flow utilised similar acoustic forcing techniques to those used by Crow & Champagne, with a horn inside the muffler to generate a fixed-frequency acoustic signal. However, for a jet Reynolds number of the order of 10^4 (based on maximum velocity and nozzle depth), inordinately-large acoustic power was necessary to generate any substantial locking of the large structure; near-field sound pressure levels of 110 dB were required for forcing at jet Strouhal numbers of 0.3 and 0.6. At this level of forcing, the particle velocities introduced by the acoustic field represent large excursions rather than small perturbations.

However, during these fixed-frequency driving experiments, a surprising effect was noticeable both from the output of hot-wires placed in a mixing-layer of the flow and from Schlieren and smoke visualisation; at moderate sound pressure levels (80 - 90 dB) the flow would "lock" for very short periods and bursts of enhanced large-scale motions would result. This transient phenomenon suggested the use of an alternative forcing method, which was to prove highly successful: a hot-wire positioned close to the lip of the jet in the unstable region of one mixing-layer was used to define the frequency (but not the amplitude) for the horn-driving signal. Using this method of positive frequency-feedback, the acoustic sound pressure level required to obtain substantial ordering of the flow reduced to approximately 70 dB for a jet Reynolds number of 10^4. In terms of particle velocities, this represents an RMS perturbation in the potential core of less than 5% of the mean velocity. Figure 1 demonstrates the marked degree of ordering of the large scale structure resulting.

The apparent lack of coherence of the forced flow beyond four jet thicknesses downstream of the nozzle in Figures 1(b) and 1(c) is a result of the visualisation method: for the jet aspect ratio used, the toroidal structures generated have significant transverse curvature, increasing as the jet develops, and the entire flow was illuminated for the photographs shown. Hot-wire measurements in the forced jet clearly show the presence of strong ordering to more than 8 nozzle thicknesses downstream (albeit with a fraction of the initial frequency and with significant variation in observed period - see #5). The level of forcing used to obtain the results shown in Figure 1 was sufficient to markedly increase the jet growth rate by the enhanced entrainment, and is significantly higher than was used in the quantitative experiments.

4 SPECTRAL MEASUREMENTS

With the reduced variation in scale of the coherent motions as a result of the positive frequency-feedback forcing, limited information is available from spectral measurements. Figure 2 shows the relative proportion of the broad-band longitudinal turbulence velocity component mean square energy contained in one-third octave bands centred on sub-multiples of the (time-averaged) forcing frequency.

The figure clearly shows the occurrence of sub-multiples of the forcing frequency, resulting from structure pairing or amalgamation, and a suggestion of some energy content corresponding to a Strouhal number of 0.6. The argument - weighted spectrum shown in Figure 3 demonstrates the broadening of the spectral peaks resulting from the increased cycle-by-cycle variation with increasing development distance.

Spectral measurements obtained under stronger forcing conditions (>90dB) show that the definition of the spectral peaks is not improved; rather, the discrete frequency sub-multiples lose definition and there is a general trend of energy

Figure 1 Jet Reynolds number 10^4, marked with paraffin smoke. Single flash illumination, exposure time approximately 10 μs

(a) Natural jet

(b) Forced jet, Strouhal number approximately 0.6

(c) Forced jet, illuminated at opposite phase of forcing signal to (b)

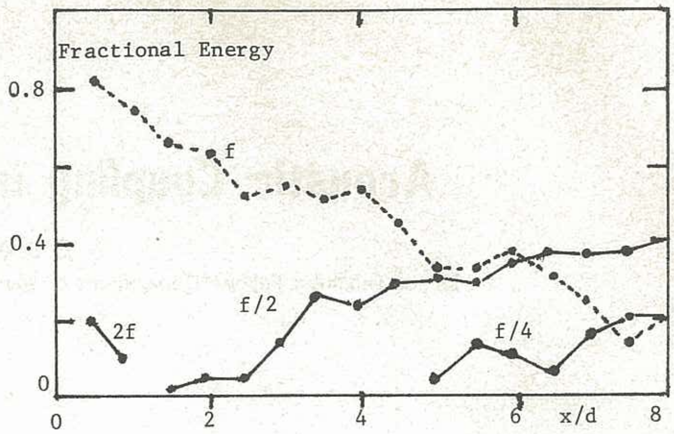

Figure 2 Relative proportions of mean-square energy contained in one-third octave bands centred on sub-multiples of forcing frequency. f represents a mean Strouhal number of 0.29. Reynolds number 10^4.

content towards the lower frequencies, indicating a spatial growth through entrainment with little or no amalgamation of the large structures.

5 DETERMINISTIC MEASUREMENT OF THE LARGE-SCALE STRUCTURE

To enable detailed examination of the large scale coherent structures in even the forced flow, some measurement technique other than straightforward digital sampling or time-averaged analogue measurement is required. Figure 4 shows typical hot-wire signals at $x/d = 0.2$ (the trigger signal providing the feedback information) and at $x/d = 2.1$.

It is clear from the figure that any frequency - filtering of the signal at $x/d = 2.1$ would lead to

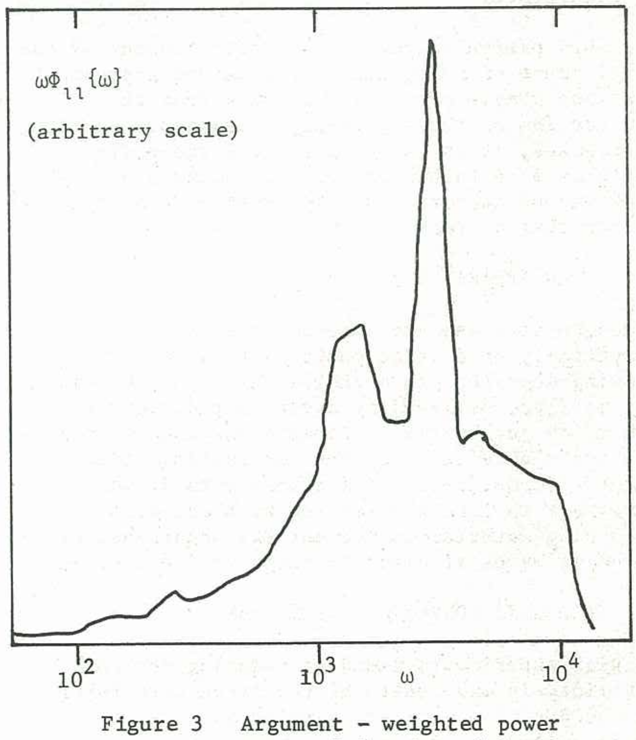

Figure 3 Argument - weighted power spectral density of longitudinal velocity fluctuations. $x/d = 3.5$, mean forcing Strouhal number ≃ 0.29, SPL at nozzle exit 80 dB.

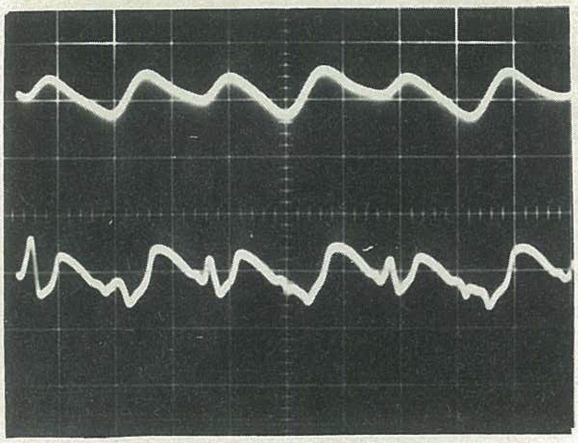

Figure 4 Hot-wire traces in forced jet. Upper trace x/d = 0.2; lower trace x/d = 2.1

a loss of detail in the deduced velocity signature of the amalgamated structure.

This difficulty would not exist if the signal were sampled on the basis of phase rather than time interval, and an ensemble velocity signature of the passing large structures could be generated complete with any fine-scale details that occurred at a particular phase in the cycle, but excluding uncorrelated "noise".

To enable such constant-phase sampling, a method based on a frequency - multiplying phase - locked loop has been developed, as shown schematically in Figure 5.

To obtain a true ensemble signature of the structure from as large a population as possible, it is crucial that the phase-locked loop remain continuously in lock.

Using a root locus analysis of the system the various gain, breakpoint and phase error parameters were determined so as to give maximum lock range for 32 phase points per cycle. The lock range possible is strongly influenced by both the frequency modulation and the frequency slew rate of the input signal, but early results obtained suggest that the method is successful to x/d = 10 for a jet Reynolds number of 10^4 with minimal feedback-forcing of 70 dB.

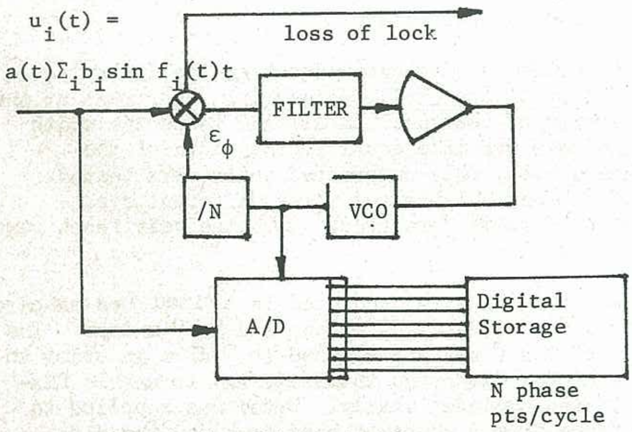

Figure 5 Schematic of constant-phase sampling method.

Figure 6 shows ensemble averages of the longitudinal and normal velocity perturbations obtained from a population of 128 cycles.

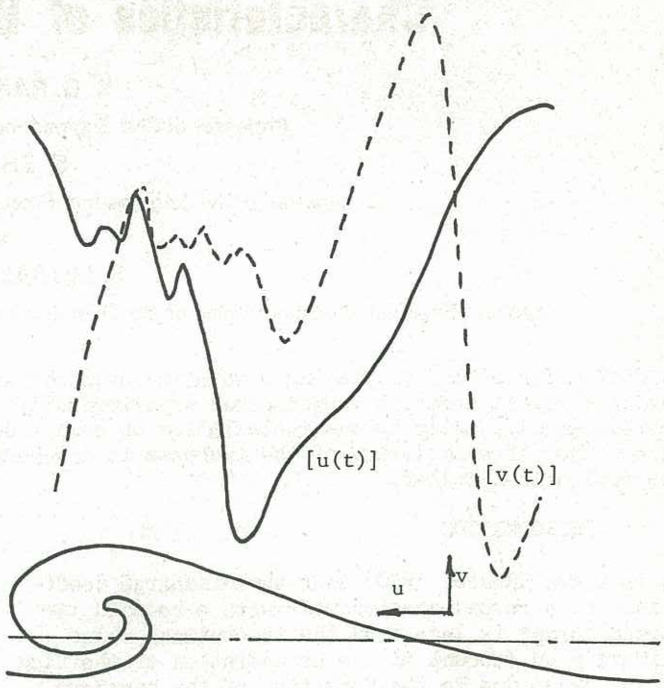

Figure 6 Ensemble-averages of velocity fluctuations; x/d = 3.5; Reynolds number 10^4; SPL = 75dB; 128 cycles. Arbitrary scales.

A noteworthy feature of the averages shown is the retention of the small-scale features.

6 CONCLUSIONS

It has been demonstrated that the use of mild acoustic forcing of a turbulent jet flow to reduce the uncertainty inherent in the large scale motions, coupled with the application of a novel sampling technique, has enabled detailed examination of some simple features of the elusive large structure.

7 ACKNOWLEDGEMENT

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