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# DYNAMIC OSCILLATION OF A QUASI-PLANAR JET

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## ABSTRACT

A naturally flapping motion of a quasi-planar, partially confined jet behind a sudden expansion into a cavity has been described by Mi et al. (1995). The investigation reported here presents data from the near field downstream from the cavity exit plane measured using hot-wire anemometers. A conditional averaging strategy is described and used to characterise the flapping motion of the jet. The contribution of the coherent flapping motion to the streamwise component of the turbulence kinetic energy is also evaluated.

## INTRODUCTION

To enhance the jet mixing characteristics for certain applications, a number of investigations of jet excitation have been carried out during recent decades. Examples of such investigations include acoustic excitations (e.g. Crow & Champagne 1971) and mechanical excitations involving moving parts (e.g. Simmons et al. 1981; Favre-Marinet et al. 1981; Davis 1982). These active excitation techniques have proved quite effective as laboratory studies, but they are less effective in practical applications due to their weight, power and maintenance requirements. For practical applications, the excitation technique needs to be simple, yet effective. In the context of this, several types of practical nozzle have been developed for the enhancement of jet mixing, such as the flip-flop jet (Viets 1975; Mi et al. 1995), the precessing jet (Nathan 1988; Nathan & Luxton 1991) and the "whistler" nozzles (Hill and Greene 1977). These devices naturally excite the jet into time-dependent oscillation. It has been recognised that such a dynamic oscillation significantly increases the large-scale mixing of the jet. The self-exciting nozzles have attracted the attention of fundamental researchers (e.g. Raman & Cornelius 1995) and have found application in industry (Nathan et al. 1992; Manias & Nathan 1993, 1994).

The present work follows previous investigations of the flapping jet by Viets (1975) and by Mi et al. (1995). The main objectives are: (1) to develop a conditional averaging technique suitable for flapping jet flows; (2) to characterise the instantaneous motion of the flapping jet; and (3) to evaluate the contribution the coherent flapping motion makes to the streamwise component of the turbulence kinetic energy.

## EXPERIMENTAL SETUP AND CONDITIONS

The experimental facility includes a plenum chamber to which various nozzles can be attached. The plenum is supplied with filtered and compressed air at pressures of up to 300 kPa at 20°C. The jet exit velocity can be varied by changing the plenum pressure. The flapping jet is generated by a novel flip-flop jet nozzle developed by Mi et al. (1995). The nozzle causes the jet to oscillate in the transverse direction in a quasi-planar fashion. Measurements reported in the present paper were made downstream from the nozzle at a Reynolds number $Re_h$ = 4800. A definition sketch and experimental arrangement is given in Figure 1.

The streamwise instantaneous velocity $U$ was measured using a 5 μm diameter tungsten hot-wire (probe 1), which was traversed laterally at several $x$-stations in the $xy$ plane

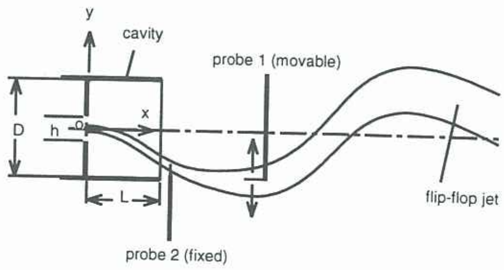



Fig.1 Definition sketch and experimental arrangement.

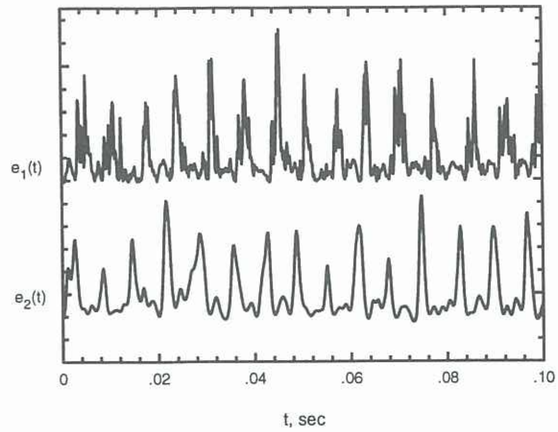



Fig.2 Voltage signals from probes 1 at $x/D = 1.72$, $y/D = -0.3$ and probe 2 at $x/D = 1.72$, $y/D = 0.3$.

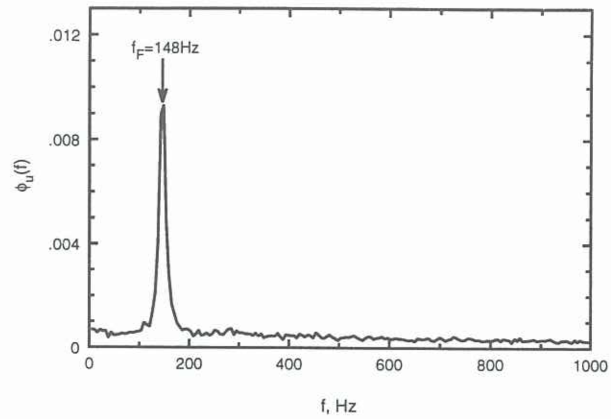



Fig.3 Spectrum of the velocity fluctuation $u$ at $x/D = 1.93$, $y/D = 0.4$.

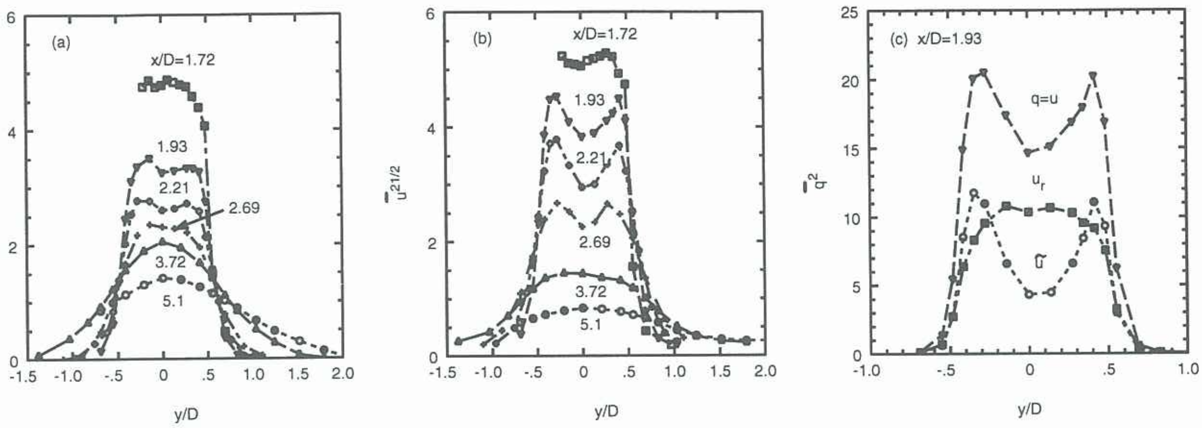



Fig.4 Lateral distributions of various velocity quantities at different $x$ stations.

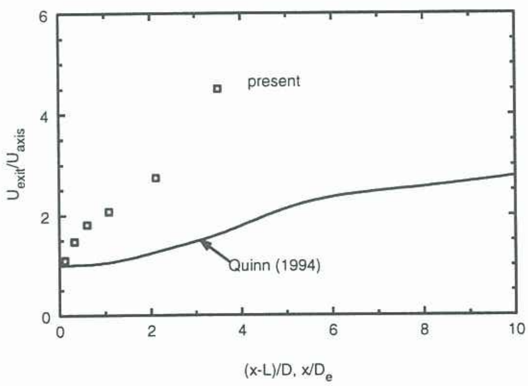


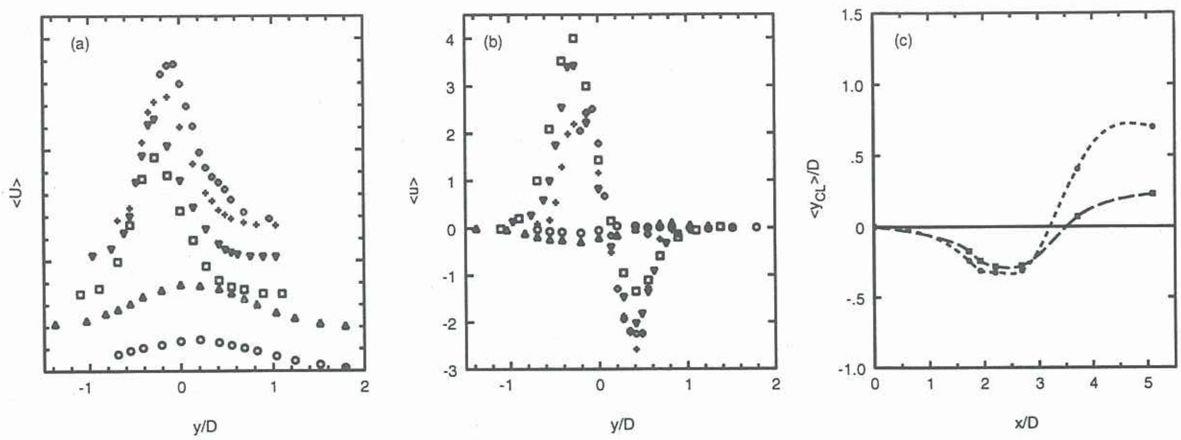

Fig.5 Streamwise variation of $\overline{U}_{exit}/\overline{U}_{axis}$ along the nozzle axis.

at $z = 0$ (Figure 1). To delineate the flapping jet, a conditional averaging technique is employed. This requires another 5 μm tungsten wire (probe 2), fixed approximately at $0.05D$ downstream from the nozzle and $0.3D$ off the axis, which was used to provide a reference for the signals from probe 1. The two wires were operated by in-house constant temperature circuits with an overheat ratio of 0.5. The signals from the circuits were offset, amplified and then digitised using a 16 channel, 12-bit A/D converter on a personal computer (Legend 486), at a sampling frequency of 5.6 kHz per channel. The filter cut-off frequency is 2.8 kHz for probe 1 and 0.5 kHz for probe 2, the reference probe. The data record duration was 15 seconds.

## CONVENTIONAL AVERAGE RESULTS

To demonstrate the flapping behaviour of the jet, output voltage signals from the two probes ($e_1$, $e_2$) are shown in Figure 2. The probes were located on opposite sides of the nozzle axis from each other. The signals $e_1(t)$ and $e_2(t)$ peak alternately with time ($t$), clearly indicating a flapping motion. The frequency ($f_F$) of the flapping, which may be inferred from Figure 2, can be determined from the $u$-spectrum $\phi_u(f)$ and is 148 Hz for the example shown in Figure 3.

The measured data of $\overline{U}$ and $\overline{u^2}^{\frac{1}{2}}$ for different values of $x$ and $y$ ($z = 0$) are plotted in Figure 4a and 4b, respectively. It is seen that $\overline{U}$ and $\overline{u^2}^{\frac{1}{2}}$ both decrease rapidly as $x$ increases. As indicated by the comparison in Figure 5, the rate of decrease in $\overline{U}_{axis}$ for the flapping jet is significantly greater than that for the non-flapping high aspect-ratio (20:1) rectangular free jet (Quinn 1994),




suggesting a relatively higher entrainment of ambient air by the flapping jet.

## CONDITIONAL AVERAGE

**I. Method**: To characterise the instantaneous behaviour of the flapping flowfield, a conditional averaging is required with an aid of a reference signal. A brief description of this method follows. The condition on which the averaging of $U$ (from probe 1) is based is the occurrence of the local maximum of $e_2$ (the output voltage signal from probe 2). In other words,

$$< U >= \frac{1}{N}\sum_{i=1}^{N} U_i \big| \max\{e_2\} \qquad (1)$$

where the angular brackets denote conditional averaging and $N$ is the total number of local maxima of $e_2$, typically 2200, used for the averaging. (Note that $< U >= \overline{U} + < u >$.) Since a reliable estimate of $< U >$ depends upon the location of the reference probe, it is important that this location be properly chosen. For the present case, the reference probe (probe 2) was placed at $x = (L+0.05D)$ and $y = -0.35D$.

The triple decomposition (Reynolds & Hussain 1972) has been applied to the instantaneous streamwise velocity $U$, i.e.

$$U = \overline{U} + \tilde{u} + u_r \,, \qquad (2)$$

where $\overline{U}$ is the time mean (or global) component, $\tilde{u}$ is the coherent jet-flapping fluctuation and $u_r$ is the jet-flapping-independent (or incoherent) fluctuation; note that

$$u = \tilde{u} + u_r \,. \qquad (3)$$

The triple decomposition (2) is utilised here as it enables the contributions of the coherent flapping and incoherent motion to the global $\overline{u^2}$ to be evaluated, viz.

$$\overline{u^2} = \overline{\tilde{u}^2} + \overline{u_r^2} \,, \qquad (4)$$

where the term $2\overline{\tilde{u}u_r}$ disappears because $\tilde{u}$ and $u_r$ are essentially uncorrelated, i.e. $\overline{\tilde{u}u_r} = 0$. The phase averaging was used for the estimate of $\overline{\tilde{u}^2}$. The phase $\phi$ was calculated from the filtered $u$-signal ($u_f$):

$$\phi = 2\pi(t - t_i) f_F \,, \; t_i - \tfrac{1}{2} f_F^{-1} \le t \le t_i + \tfrac{1}{2} f_F^{-1} \,, \qquad (5)$$

where $t_i$ corresponds to the instant when the local maximum of $u_f$ occurs; $u_f$ is the signal of $u$ which was digitally band-pass filtered with the centre frequency of the filter set equal to $f_F$, the flapping frequency as determined from the frequency spectrum. The phase-dependent coherent fluctuation is

$$\tilde{u}(\phi) = \frac{1}{N}\sum_{i=1}^{N} u(\phi) \,;$$

$\overline{\tilde{u}^2}$ was then estimated by averaging $\tilde{u}(\phi)$ from $\phi = -\pi$ to $\pi$, i.e.

$$\overline{\tilde{u}^2} = \frac{1}{2\pi}\int_{-\pi}^{\pi} \tilde{u}^2(\phi)\, d\phi \,.$$

**II. Results and Discussion**: Lateral profiles of $< U >$ and $< u >$ for different values of $x$ are plotted in Figure 6a & b, respectively. (Note that, for clarity, the $< U >$ curves have been displaced from each other.) Unlike $\overline{U}(y)$, $< U >(y)$ is not symmetric with respect to the nozzle axis and peaks at a different $y$ location for each value of $x$. Also, $< u >(y)$ varies with $y$ in an antisymmetric fashion. Such behaviour of $< U >$ and $< u >$ points to a flapping motion of the jet. To examine the average trajectory of the jet when its centre passes through probe 2, the $y$ location of $< U >_{max}$ (the maximum of $< U >$), denoted by $< y_{CL} >$, was obtained from the data presented in Figure 6a. The "flag-like" flapping of the jet is clearly demonstrated by the streamwise variation of $< y_{CL} >$ (Figure 6c). Since $< u >$ and $\overline{U}$ do not peak at the same $y$-location and $< U >= \overline{U} + < u >$, $y(< u >_{max})$ differs from $< y_{CL} >$, as indicated in the figure.

Fig.6 Lateral distributions of $< U >$ and $< u >$; and streamwise variation of $< y_{CL} >$. (a) $< U >$; (b) $< u >$; (c) $< y_{CL} >$. ◆, $x/D$ = 1.72; +, 1.93; ▼, 2.21; □, 2.69; ▲, 3.72; ○, 5.1. -----, $< y_{CL} >$; ........, $y(< u >_{max})$.

The phase averages $\overline{\tilde{u}^2}$ and $\overline{u_r^2}$ for all values of $x$ were obtained using the method described above. Shown in Figure 4c, for example, are lateral distributions of $\overline{\tilde{u}^2}(y)$ and $\overline{u_r^2}(y)$ for $x/D = 1.93$; for comparison, the distribution of $\overline{u^2}$ at the same value of $x$ is included. As expected,

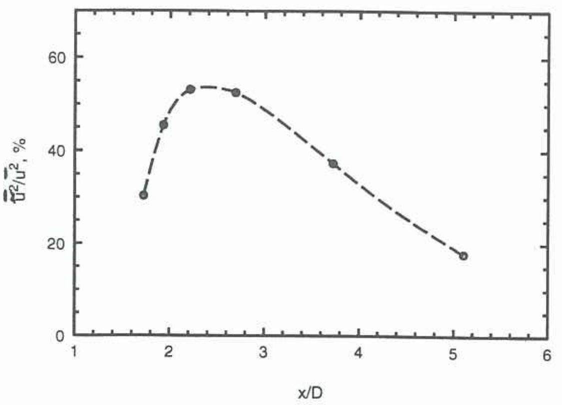



Fig.7 Streamwise variation of $\overline{\tilde{u}^2} / \overline{u^2}$ at $y = < y_{CL} >$.

$\overline{\tilde{u}^2}$ exhibits strong double peaks away from the axis (at $y/D \approx \pm 0.4$), while $\overline{u_r^2}$ changes only slightly within a wide range of $y$ around $y = 0$. (Note that, in fact, it is the case for $x / D < 3.72$.) This indicates that the contribution the flapping motion makes to $\overline{u^2}$ generally increases with $|y|$ in the central main flow region. As a result of such a contribution, both $\overline{U}$ and $\overline{u^2}$ are also double-peaked. To quantify the fraction this contribution takes in $\overline{u^2}$ and to examine its streamwise variation, we estimated the ratio $\overline{\tilde{u}^2} / \overline{u^2}$ for $y = < y_{CL} >$ at all measured $x$ stations, as shown in Figure 7. It is of interest to note that the magnitude of the ratio does not decrease monotonically as $x$ increases; its maximum ($\approx$55%) occurs between $x / D = 2.2$ and 2.7. This is consistent with the observation in Figure 6b that $< u >$ reaches its highest level at $x / D \approx 2.7$, rather than at 1.72, the $x$-location of probe 1 nearest probe 2. Perhaps it is worth noting here that the ratio $\overline{u^2}^{1/2} / \overline{U}$ is also relatively high at that $x$ value (see Figure 4a & b). When $x / D \geq 5$, the flapping motion is significantly attenuated and, consequently, $\overline{\tilde{u}^2}$ becomes less important (e.g. $\overline{\tilde{u}^2} / \overline{u^2} < 20\%$). It is anticipated that the jet would further develop to behave like a normal, non-excited free jet in the far field. The data for $x / D = 5.1$ (Figure 4) appears to support this anticipation.

## CONCLUSIONS

The quasi-planar, partially confined turbulent jet from a nozzle of a particular geometry, developed by Mi et al. (1995), flaps from side to side in the transverse direction. This flapping motion has been clearly demonstrated using a conditional averaging technique described in the present paper. The coherent flapping of the jet contributes significantly to the conventionally defined turbulence energy in the near flowfield. However, this contribution decays rapidly as the jet proceeds downstream and becomes negligible at a distance greater than about 5*D* from the nozzle.

## ACKNOWLEGEMENT

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