14th Australasian Fluid Mechanics Conference
Adelaide University, Adelaide, Australia
10-14 December 2001

Control of an Axisymmetric Jet Using a Passive Ring

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Abstract
This study examines the near field mixing layer development (up to x/D = 5 where x is the longitudinal distance and D is the nozzle exit diameter) of an axisymmetric jet, which is disturbed by placing a thin wire ring axisymmetrically in the mixing layer close to the nozzle exit (0.1≤ x/D ≤ 0.5). The introduction of the ring in the mixing layer results in significant changes in the jet development, namely a reduction in both the mixing layer growth rate and jet spread rate. The turbulence level in the mixing layer is substantially reduced for both longitudinal and transverse fluctuations (approx 20% and 15% respectively). In addition to these reductions the normalised distributions of mean velocity, longitudinal and transverse velocity fluctuations as well as the skewness and flatness factor of these fluctuations, all exhibit improved similarity.

The investigation of the effects of ring position in the axial direction and varying the jet Reynolds number (and thus the wire Reynolds number of the ring) indicates that these variations yield nearly identical changes to the characteristics of jet, which suggests this method of jet control is robust.

Introduction
The control of turbulence in jet flows has been the subject of a large number of studies, with many different methods, both active and passive, employed to modify the turbulence characteristics of jet flows.

Acoustic excitation has been used extensively to both increase, Crow and Champagne [1], and suppress, Zaman and Hussain [5], turbulence levels. Reductions in turbulence have been achieved through the introduction of small diameter cylinders in the mixing layers of a plane jet, Rajagopalan and Antonia [2]. Schrober and Fernholz [3] used a trip wire to suppress the formation of large structures in a wall jet.

Tong and Warhaft [4] examined the development of an axisymmetric jet, up to x/D = 25, modified by inserting a fine wire ring in the shear layer of the jet. The insertion of the ring resulted in a significant reduction in RMS longitudinal velocity fluctuations, a reduced spatial growth rate, a shift in the virtual origin of the jet and a suppression of vortex formation and pairing.

The present work extends the investigation of Tong and Warhaft, by examining the effect of introducing a fine wire ring on longitudinal (u') and transverse velocity (v') fluctuations, higher order moments of velocity fluctuations (skewness and flatness factor) and the Reynolds shear stress, in the initial region of the jet (x/D ≤ 5).

Experimental Conditions
The set-up consists of a 20.5mm axisymmetric nozzle. Air is supplied by two coupled centrifugal fans operating in parallel and driven by a D.C. motor. The speed of the fans, and thus the jet exit velocity, can be varied by changing the motor supply voltage. Air enters a settling chamber and passes through a series of screens and honeycomb before entering the nozzle contraction, which has a diameter ratio of 6:1. The ring used to disturb the mixing layer is constructed using a 0.5mm diameter wire and has an outer diameter of 20mm. Measurements were performed using a 2.5μm X-wire probe operated in constant temperature mode. The majority of detailed measurements were carried out at a Reynolds number ($Re_D = U_j D/\nu$, where U_j is the jet exit velocity, D is the nozzle diameter and ν is the kinematic viscosity of air) of 23500 with the ring positioned concentrically with the nozzle exit at x/D = 0.15. Some additional measurements at different Reynolds numbers and ring positions were also carried out to check the influence of Re_D and ring location.

Jet Initial Conditions
Figure 1 shows normalised boundary layer profiles at the nozzle exit obtained using a miniature single wire probe 0.5mm upstream of the nozzle exit plane (x/D = -0.025). Calculation of the shape factor for these profiles shows the boundary layer to be laminar at the exit velocities examined. These profiles show a small departure from the Blasius solution for a laminar boundary layer. This deviation from Blasius profile could be due to the presence of a small, favourable pressure gradient in the flow through the nozzle contraction.

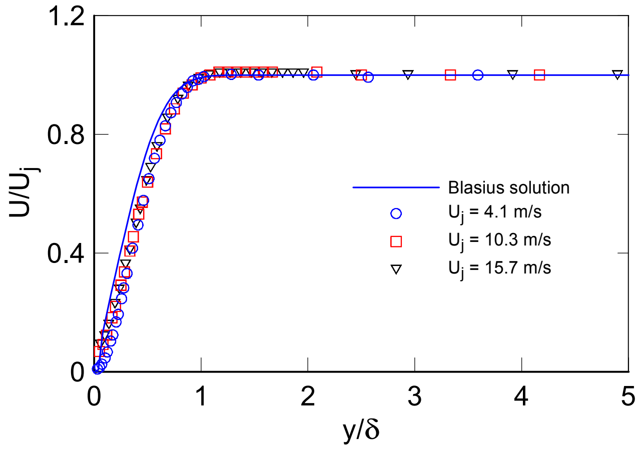

Figure 1. Normalised boundary layer profiles at x/D = -0.025

U_j (m/s)	δ^* (mm)	θ (mm)	H	R_θ	Free Stream Turbulence %
4.1	0.813	0.275	2.96	751	0.93
10.3	0.444	0.171	2.60	1174	0.83
15.7	0.360	0.144	2.49	1507	0.82

Table 1. Nozzle exit boundary layer statistics.

Mean Velocity Distribution
Figure 2 shows that the disturbed flow exhibits a rapid increase in mixing layer thickness behind the ring but a reduced rate of mixing layer growth thereafter resulting in a reduction in mixing layer thickness for x/D > 1.

This decreased rate of mixing layer growth is mainly the result of a reduction in the spread rate for the jet. However, a small increase in the width of the potential core is also observable particularly downstream of x/D = 4. This increase in potential core width is consistent with the results obtained by Tong and

Warhaft [4]; their mean velocity distribution on the jet axis indicates an increase in the length of the potential core for the modified flow.

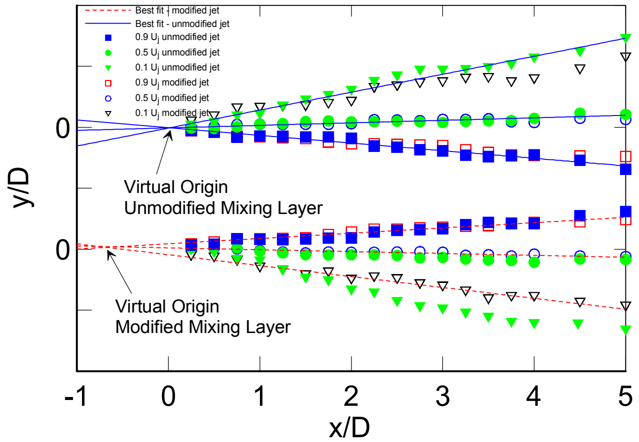

Figure 2. Mixing layer growth for natural and modified jet.

The modified flow also exhibited a shift in the position of the virtual origin from x/D = 0 to x/D = -0.6. This upstream shift in virtual origin can clearly be seen in Figure 2 with the rapid increase in the mixing layer thickness immediately downstream of the ring and a reduced mixing layer growth rate combining to move the virtual origin upstream. This result differs from that obtained in [4] where the virtual origin was seen to move from x/D = 0 downstream to x/D = 3. This apparent difference is due to the fact that the method used in [4] calculates a virtual origin for the jet, based on centreline velocity between x/D = 5 and 25, while the method used here calculates the virtual origin of the jet mixing layer, based on iso-velocity contours.

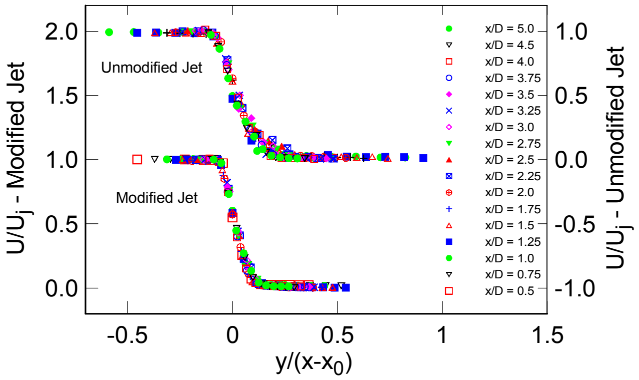

Figure 3. Normalised mean velocity distribution (U).

As can be seen in Figure 3 the modified flow shows increased similarity, consistent with a linear mixing layer growth rate, particularly in the region x/D ≤ 1.25 where similarity of the undisturbed flow was relatively poor.

RMS Velocity Fluctuations

The modified flow exhibits maximum reduction of approximately 20% in u' (Figure 4) and 15% in v' (Figure 5). The disturbed flow showed enhanced similarity for the normalised (by jet exit velocity U_j) distributions of both u' and v' particularly on the low speed side of the mixing layer.

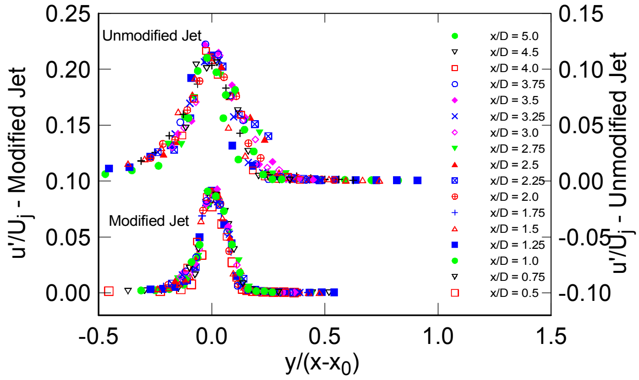

Figure 4. Distribution of RMS longitudinal velocity fluctuations (u').

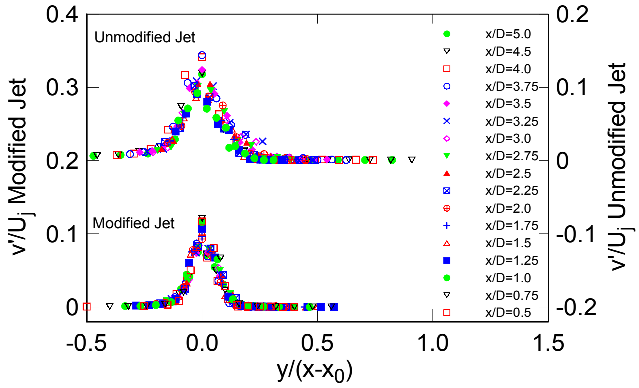

Figure 5. Distribution of RMS transverse velocity fluctuations (v').

Skewness and Flatness Factor Distributions

The distributions of skewness and flatness factors for both longitudinal and transverse velocity fluctuations were obtained in the modified and unmodified flows

The modified flow shows a significant enhancement in the similarity of the distribution of skewness factor, for both longitudinal (S_u, Figure 6) and transverse fluctuations (S_v, Figure 7), in the mixing layer. As was the case for the mean and RMS distributions, the increase in similarity is most pronounced on the low speed side of the mixing layer. An increase in magnitude was exhibited for most locations throughout the mixing layer. Such an increase was also evident in S_v.

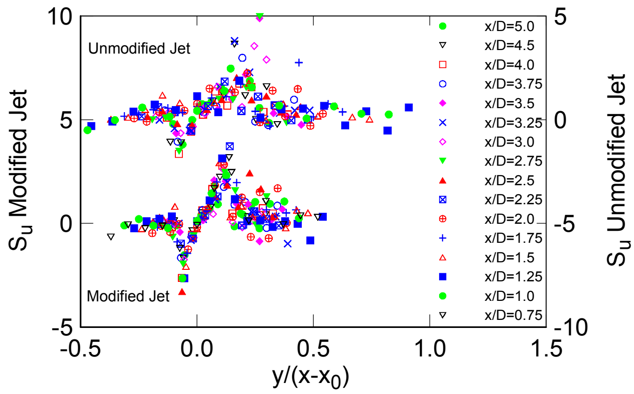

Figure 6. Skewness factor distribution for longitudinal velocity fluctuations.

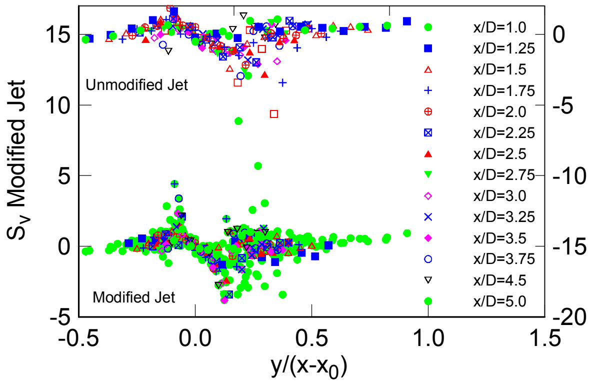

Figure 7. Skewness if v

The flatness factor distributions of u and v display enhanced similarity in the modified flow. Both flatness factor distributions exhibited a reduced magnitude on the low-speed side of the mixing layer and an increased magnitude on the high-speed side resulting in increased symmetry across the mixing layer (Figures 8 and 9).

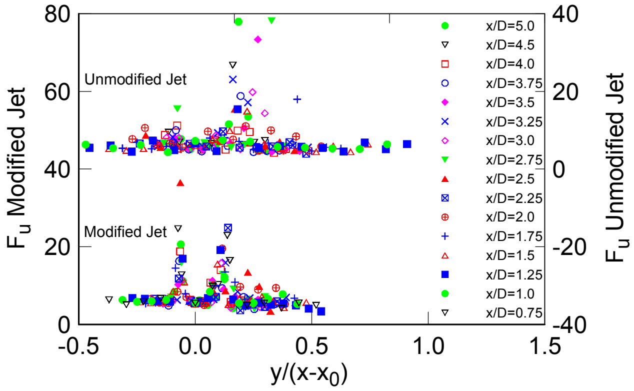

Figure 8. Flatness factor of u.

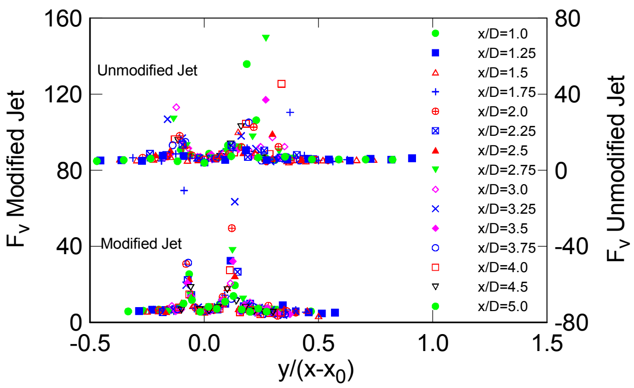

Figure 9. Flatness factor of v.

Reynolds Shear Stress

The levels of Reynolds shear stress throughout the mixing layer (Figure 10) are substantially reduced, with a maximum reduction of 19%. The distribution of shear stress across the mixing layer of the modified flow exhibited increased similarity, particularly on the low speed side of the mixing layer.

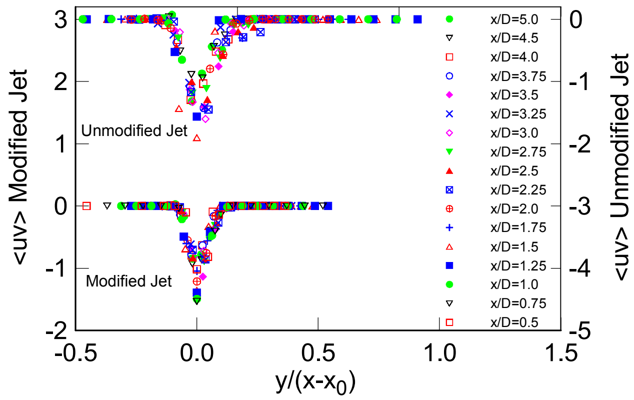

Figure 10. Reynolds Shear Stress.

Effect of Ring Position

Figure 11 shows the effect on the mean velocity distribution at x/D = 3 caused by varying the downstream position of the ring over a range of 0.15 ≤ x/D ≤ 0.5. It is clear that altering the ring position over this range caused very little variation in the mean velocity distribution.

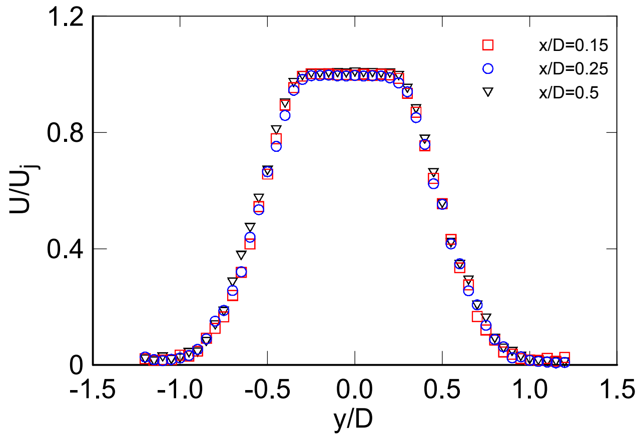

Figure 11. Effect of varying the axial location of ring on the mean velocity distribution at x/D = 3.

The effect of altering the ring position on the distribution of longitudinal and transverse velocity fluctuations was also examined by plotting their distributions as measured at x/D = 3 (not shown here). In both cases, as with the mean velocity, there was no significant variation between the distributions obtained for each ring position. From these results it is apparent that the distributions are effectively independent of ring position over the range of positions investigated.

Effect of Jet Reynolds Number

The jet Reynolds number was varied from 11450 to 23500 and the effect of this variation examined at x/D = 3.No significant variation in the distribution of U/U_j, u'/U_j (Figure 12) or v'/U_j was observed as a result of varying Reynolds number over this range.

This tends to confirm the conclusions of Tong and Warhaft, 1994 that, the modification of the mixing layer is driven primarily by the alteration in the mixing layer profile and that the ring vortex shedding frequency does not seem to play a significant role in the modification.

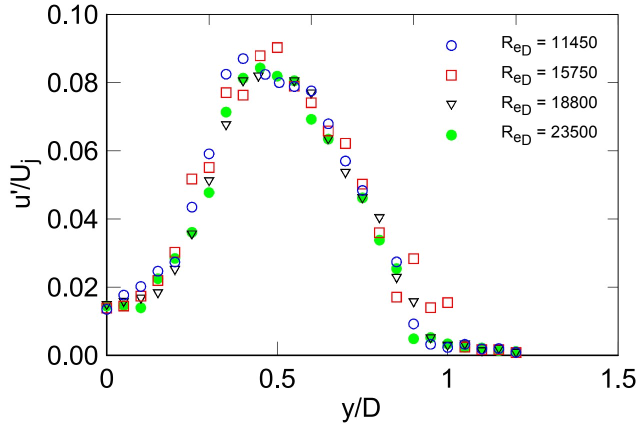

Figure 12. Effect on distribution of u' of varying jet Reynolds number Re_D.

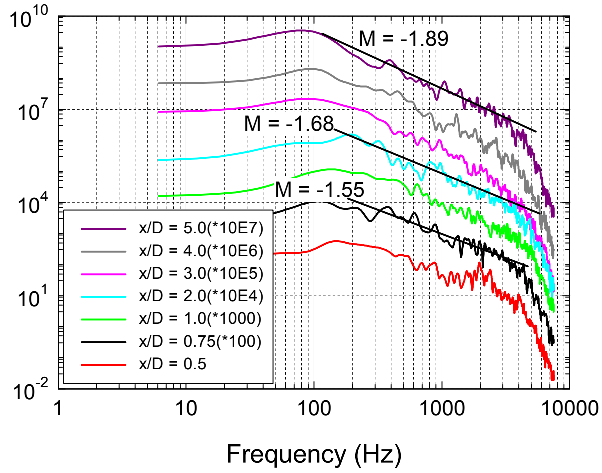

Figure 14. Evolution of mixing layer spectra for modified jet.

Mixing Layer Spectra

Figures 13 and 14 show frequency spectra for a range of downstream locations for the unmodified and modified flows respectively. All the samples used in both figures where taken at transverse locations such that $U/U_j = 0.5$.

Figure 13 clearly shows dominant frequencies associated with vortex formation in the region $x/D \leq 1.5$, for the unmodified jet. The evolution of the mixing layer spectra with downstream position indicates the occurrence of two vortex-pairing events.

The spectra for the modified flow, as shown in, do not display the presence of dominant frequencies, indicating that the presence of the ring suppresses the formation of large scale organised structures in the mixing layer.

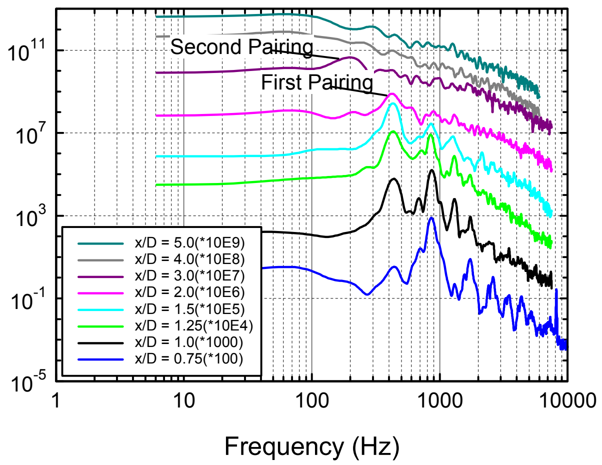

Figure 13. Evolution of mixing layer spectra for unmodified jet.

Conclusions

The insertion of a thin ring axisymmetrically in the mixing layer of a circular jet close to the nozzle exit modifies the jet structure in a substantial manner.

The modified flow exhibits increased similarity throughout the mixing layer particularly in the region $x/D = \leq 1.25$ where similarity in the unmodified flow is poor. This increased similarity is present not just in the mean velocity distribution but extends to higher order moments e.g. RMS, S and K, of the velocity fluctuations as well as Reynolds shear stress.

Mixing layer growth rate of the modified jet is substantially lower than that of the unmodified jet. This reduced growth rate is due predominantly to a decrease in the spread rate of the jet. A small increase in the width of the potential core of the jet has been observed.

Turbulence intensities within the jet mixing layer, in both longitudinal and transverse directions, are substantially reduced, by 20% and 15% respectively.

Different ring positions and Reynolds numbers yield nearly identical changes to the jet characteristics. This indicates that this method of modification is robust thus lending itself to industrial applications.

The suppression of vortex formation achieved with this modification could find application in situations where aerodynamic jet noise reduction is desired.

Potential applications exist where a reduction in width of jet is required.

Acknowledgements

The continuing support of the Australian Research Council is acknowledged.

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