TURBULENCE CONTROL IN A PLANE JET USING A PIEZOELECTRIC EXCITATION DEVICE

R. Parker, S, Rajagopalan, R.A. Antonia.
Department of Mechanical Engineering, University of Newcastle.
University Drive, Callaghan, NSW, 2308.
ross.parker@studentmail.newcastle.edu.au

ABSTRACT

This study is concerned with the development and evaluation of a localised method of shear flow excitation in a plane jet using piezoelectric actuators. Piezo excitation results in an increase in u' and v' and promotes the formation of vortices in the initial region of the jet. When compared with global excitation of the flow, for example via acoustic excitation, piezoelectric actuation is able to provide a comparable level of flow modification but with a significantly lower power input. The effect of excitation on the distribution of $\bar{U}$, u' and v' as well as mixing layer spectra is examined using hotwire anemometry and flow visualization. These results are compared with those observed when applying acoustic excitation in the same test facility.

INTRODUCTION

Control of jet turbulence has been widely investigated, driven in many instances by technological requirements for modification of mixing, entrainment or noise characteristics.

The presence of orderly vortical structures in the jet shear layer (Crow & Champagne 1971), and recognition of the role the merging of these structures plays in determining the shear layer growth rate of the jet, (Brown & Roshko 1974), has led to several studies on the use of excitation to control jet turbulence. Methods of excitation that perturb the entire flow, predominantly acoustic excitation, have been used extensively in both axisymmetric and plane jets.

Lepicovsky (1989) has suggested that an increase in vertical velocity fluctuations i.e. fluctuations in the y-direction, in the shear layer enhances vortex formation and increases mixing. We seek to exploit this suggestion with the use of piezoelectric actuators, developed for this study, which directly perturb the shear layer in the y-direction.

The motivation for investigating this type of excitation is twofold. Firstly, the ready availability of materials such as piezoelectric crystals makes the manufacture of compact actuators suitable for integration into nozzles easily achievable. Secondly, we believe that the direct perturbation of the jet shear layer, in the y-direction, at the nozzle exit has the potential to achieve substantial jet control with minimal energy input.

Various forms of localised mixing layer excitation has been used in a number of previous studies. Suzuki et al. (1999) successfully used electromagnetic flap actuators to achieve significant flow control in a circular jet. The configuration of these actuators is similar to that used in this study in that they directly perturb the mixing layer in the y-direction at the nozzle exit plane. Wiltse and Glezer (1998) used piezo electric actuators for flow control in a jet emanating from a square conduit. The configuration of that actuators differs significantly from those in the current study. In their study they perturb the mixing layer in the streamwise direction and the excitation applied using a high frequency carrier (the low frequency components were applied via frequency modulation). The actuators were also positioned at a short distance downstream of the exit plane.

In this study we examine the effect of piezo excitation on the mean velocity, turbulence levels and the spectra. Also the effect of acoustic excitation is compared with that for piezoelectric excitation.

EXPERIMENTAL SET-UP

The plane jet is 10mm high with an aspect ratio of 6.3 and operated in air at an exit velocity of 10m/s. The test facility is fitted with a speaker in the settling chamber that allows acoustic excitation to be applied to the jet.

The piezo excitation devices consist of a layer of piezo crystal, 0.2 mm thick, laminated to strips of brass shim, 0.05 mm thick, and mounted so as to form the full width of both sides of the exit section of the nozzle (**Figure 1**).

Electrical excitation of the piezo crystal causes it to expand or contract depending on the polarity of the applied voltage. The strips of brass shim serve to restrain the movement of one side of the crystal sheet, in one direction, causing an expansion in the crystal to flex the device away from the jet centre line and a contraction to it flex toward the centre line. The application of a sinusoidal voltage causes the tip of the devices to vibrate in a direction normal to the mean flow (**Figure 2**). The magnitude of deflection depends on the amplitude of the A.C. excitation voltage and its frequency.

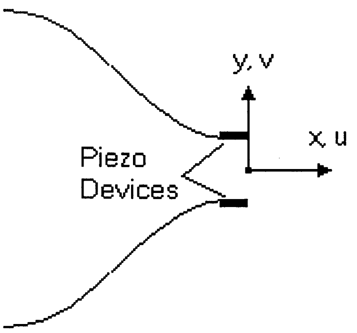

Figure 1. Sketch of plane jet contraction showing excitation device at nozzle exit.

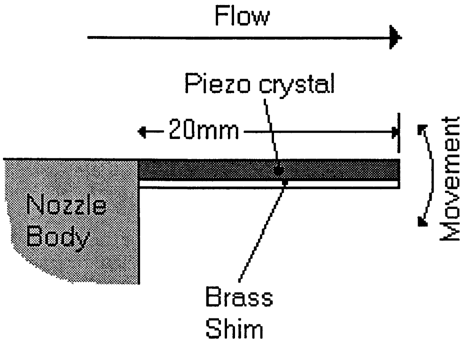

Figure 2. Excitation device, detail.

Initial measurements were carried out with excitation applied to one side of the jet only. Having established that this method of excitation could significantly modify the jet mixing layer development, an idential second piezo excitation device was constructed and fitted to the opposite side of the nozzle.

Measurements were made with an X-wire probe, the etched portion of which had a diameter of 2.5µm, operated in constant temperature mode. A single hot wire probe was positioned in the jet mixing layer at x/H=2 sufficiently displaced in the spanwise direction from the measurement plane to avoid probe interference effects. The outputs of the hot wires, as well as the excitation voltage, were digitized at a sampling frequency of 20kHz using a PC30 A to D board. The X-wire probe was positioned using a 2-axis automated traverse system with a minimum resolution of 0.02mm. Sinusoidal excitation waveforms were generated using a Hewlett Packard 3312A function generator.

Flow visualization images were obtained by introducing smoke at the inlet of the jet facility. The flow was illuminated using an argon laser, 2W output, and appropriate optics to create a 1mm thick light sheet in the x-y plane. The resulting images were captured using a CCD camera at a shutter speed of 1/2000 sec and stored on video.

Determination of excitation levels

The excitation level used for each of the three excitation regimes was determined from observation of the output of the single hotwire placed in the mixing layer at x/H = 2. In both the acoustic and piezo excitation regimes a critical level of excitation was observed below which the output was independent of the excitation signal and at or above this level the output waveform was strongly correlated with the excitation waveform. In all cases presented here the excitation applied was maintained at this critical level. The power input to the excitation devices was measured at 0.2W for the acoustic excitation and 0.067W for the piezo excitation.

RESULTS

Velocity profiles were measured in the range 0.25 to 5.0 in increments of 0.25H.

The following four operating conditions were examined:

- Jet centerline velocity, U_j = 10m/s, No Excitation.
- U_j = 10m/s, Piezo Excitation at 420Hz
- U_j = 10m/s, Piezo Excitation at 645Hz
- U_j = 10m/s, Acoustic Excitation at 645Hz

Examination of spectra in the initial region of the unexcited jet shear layer indicated a 420Hz to be the frequency at which the power spectral density of u was maximum. Excitation was applied at 420Hz to examine the effect of enhancing this naturally occurring frequency.

The 645Hz excitation frequency was chosen after qualitative observation of mixing layer development over a range of frequencies showed the presence of highly organized large-scale motion at this frequency.

Effect of excitation on the initial mixing layer momentum thickness

Initial mixing layer momentum thickness is recognised as playing an important role in jet development (Ho and Huerre, 1984). In order to determine the effect of piezo excitation on mixing layer in the initial region, mean velocity distributions were measured at x/H=0.25 without excitation, and with excitation at 645Hz.

Phase averaging techniques were used to obtain mixing layer mean velocity profiles at 20 instants per excitation cycle. The momentum thickness Θ

was calculated for each case (**Figure 3**) and shows a negligible variation over an excitation cycle. It is clear from these results that this method of excitation does not significantly alter the initial jet mixing layer momentum thickness. Inspection of the phase averaged velocity profiles shows that, although the profile is displaced in the y-direction, the shape of the profile does not alter significantly from that of the unexcited jet.

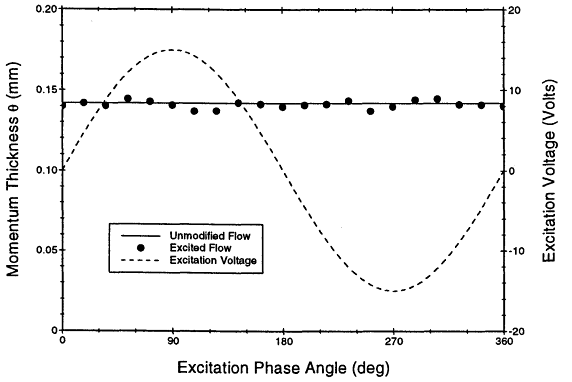

Figure 3. Effect of excitation on momentum thickness

Mixing layer development

Estimates of the mixing layer growth rate were obtained by plotting Ū contours for Ū/Uj = 0.1, 0.5 and 0.95, (Figure 4). It is clear that while both acoustic and piezo excitation promote an earlier expansion of the mixing layer, i.e. the mixing layer virtual origin is moved upstream, piezo excitation has a stronger influence on mixing layer growth than acoustic excitation. Although both acoustic and piezo excitation at 650Hz lead to an upstream movement of the virtual origin the mixing layer growth rate is equal to that of the unexcited flow. In the case of excitation at 420Hz the mixing layer growth rate is substantially lower such and at x/H = 5 the mixing layer width is not significantly larger than that of the unexcited flow.

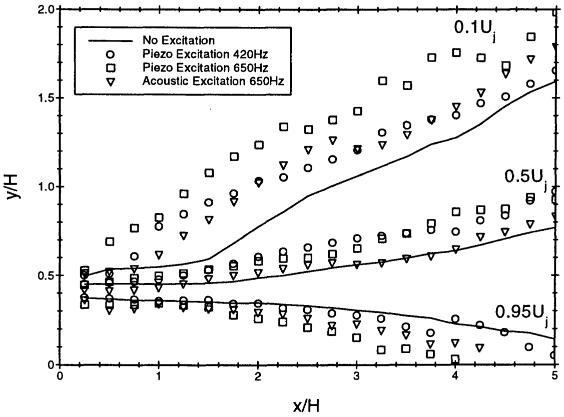

Figure 4. Mean Velocity Contours for All Conditions Investigated.

Figures 5 to 8 show the contour of u'/U$_j$, (longitudinal velocity fluctuation) for each of the flow regimes examined. For all the excited flows u'/U$_j$ is modified significantly. Of particular significance is the pocket of high turbulence intensity produced by piezo excitation in the centre of the mixing layer, near y/H = 0.5. The levels of u'/U$_j$ observed in this region are approximately 30% higher than those observed at any location in the unexcited flow.

From a comparison between distributions of u'/U$_j$ (Figures 6 and 7) for the two piezo excitation frequencies, it is apparent that the pocket of high intensity produced by the 645Hz excitation is more concentrated and is located upstream compared to that produced by the 420Hz excitation.

The overall distribution of u'/U$_j$ for the acoustic excitation is similar to that for the piezo excitation at the same frequency; there are however two notable differences. Firstly, the region of high turbulence intensity observed for the piezo excitation is completely absent. Secondly, the entire distribution is displaced downstream with the distribution for the piezo excitation developing earlier than that for the acoustic excitation.

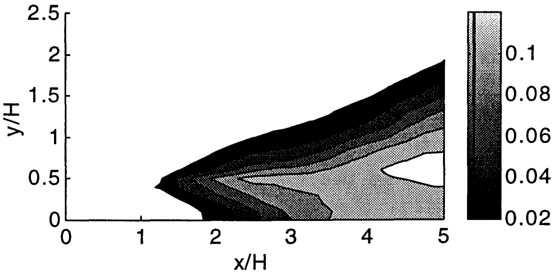

Figure 5. u'/U$_j$ Contours, No Excitation

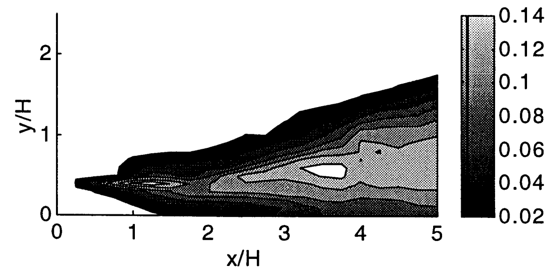

Figure 6. u' Contours. Piezo Excitation at 420Hz.

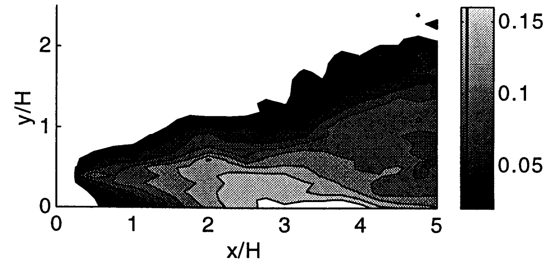

Figure 7 u'/U$_j$ Contours. Piezo Excitation at 645Hz.

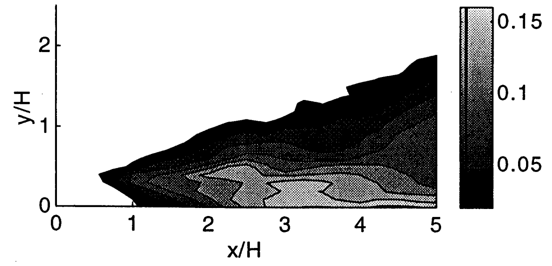

Figure 8. u'/U$_j$ Contours. Acoustic Excitation at 645Hz.

Figures 9 to 12 show distributions of v'/U$_j$, for each of the flow regimes. Similar to the u'/U$_j$ distributions, all the excited flows display significant modification. For both of the piezo excitation cases, a region where v'/U$_j$ is large, similar to that exhibited in the u'/U$_j$ distributions is present, but for the 645Hz excitation case this region extends downstream by 1H more than for u'/U$_j$.

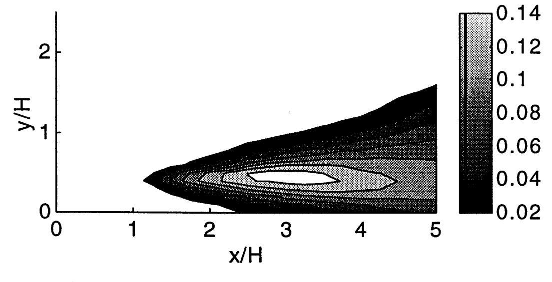

Figure 9. v'/U$_j$ Contours. No Excitation.

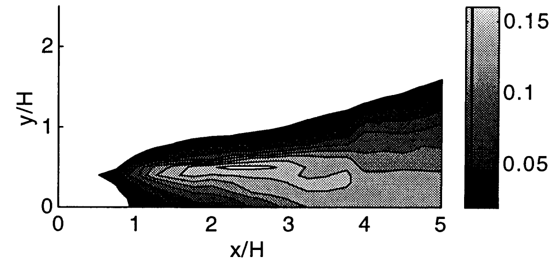

Figure 10. v'/U$_j$ Contours. Piezo Excitation at 420Hz.

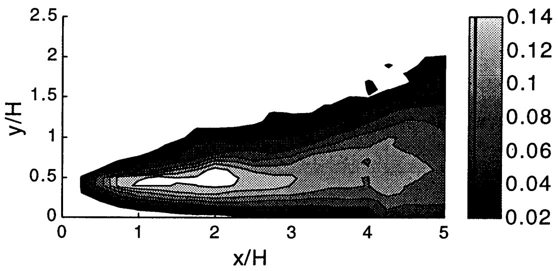

Figure 11. v'/U$_j$ Contours. Piezo Excitation at 645Hz.

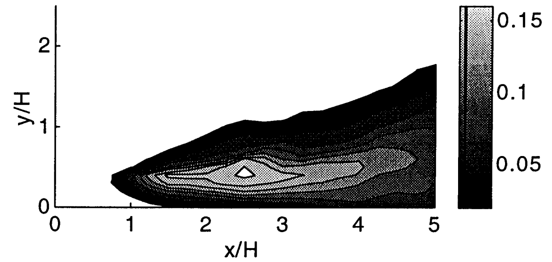

Figure 12. v'/U$_j$ Contours. Acoustic Excitation at 645Hz.

Spectra

Figure 13 shows the mixing layer spectra at x/H = 1.25 for the unexcited jet, where the mean velocity contours and the flow visualisation indicate that the mixing layer begins to expand and organised large scale stuctures fist appear. This plot shows that the dominant frequency is 420Hz.

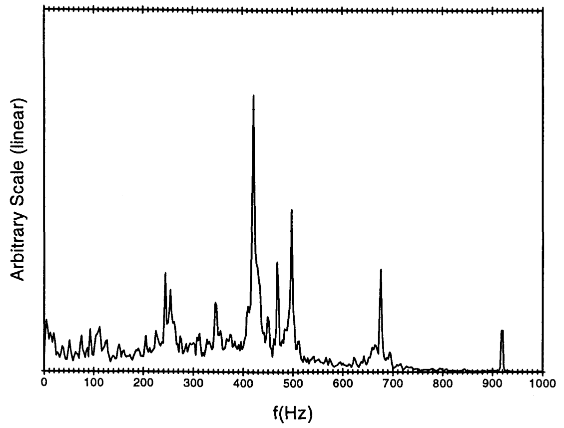

Figure 13. Initial Region Mixing Layer Spectrum. No Excitation.

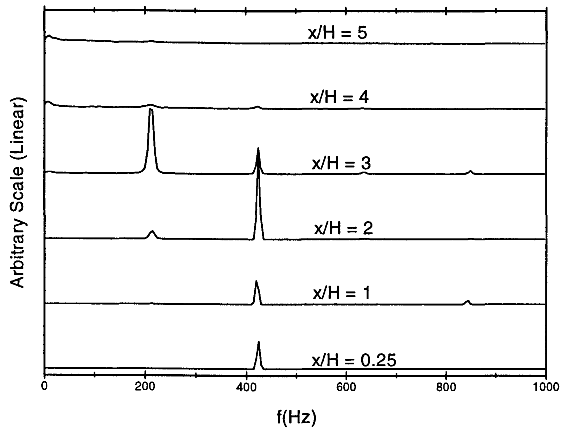

Figure 14. Mixing Layer Spectral Evolution for Piezo Excitation at 420Hz

Figure 14 shows the evolution of mixing layer spectra, for increasing values of x/H, with piezo excitation at 420Hz. It is apparent from the spectra that the large scale organized structures are formed at the excitation frequency and undergo one pairing process before the organized structures lose their coherence. The occurrence of a single vortex pairings event can be infered from the transfer of turbulent energy from the excitation frequency to the its subharmonic, 210Hz, at x/H ≈ 3.

Figure 15 shows the evolution of mixing layer spectra when piezo excitation is applied at 645Hz. The occurrence of two vortex pairing events can be infered from the progressive transfer of turbulent enery to the subharmonic, at ~320Hz, and then to the 2nd subharmonic, at ~160Hz, of the excitation frequency as x/H increases.

Figure 16 shows the mixing layer spectral evolution for acoustic excitation at 645Hz. Comparison with that for piezo excitation at the same frequency indicates that the formation of organized large scale structures occurs further downstream. Again the occurrence of two vortex pairing events can be inferred from the transfer of turbulent energy from the excitation frequency to its sub-harmonic and then to its 2nd sub-harmonic.

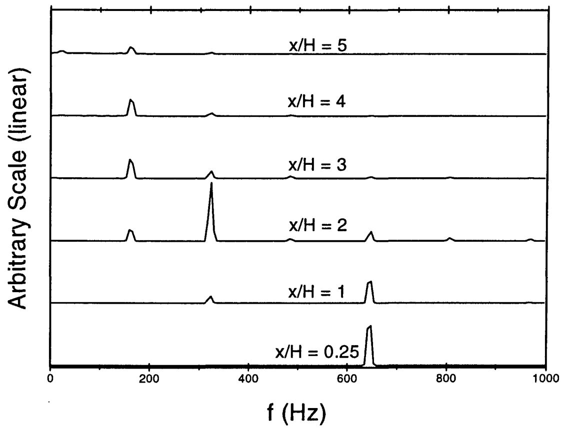

Figure 15. Mixing Layer Spectral Evolution for Piezo Excitation at 650Hz.

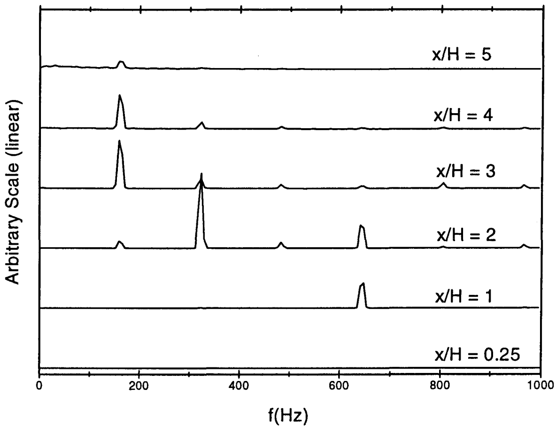

Figure 16. Mixing Layer Spectral Evolution for Acoustic Excitation at 645Hz.

Flow Visualization

Figures 17 to 19 provide visual evidence of the effect of piezo excitation on the development of the jet. These images confirm that piezo excitation results in an expansion of the jet further upstream than for the unexcited flow. They suggest that the mechanism for this expansion is the production of vortices significantly upstream compared to their occurence in the unexcited flow.

Comparison of figures 18 and 19 confirms that the effect of excitation at 645Hz is sustained much further downstream than that of the excitation at 420Hz as indicated by the mean velocity profiles (Figure 4). Comparison between figures 17, 18 and 19 also indicates that the large-scale organisation is maintained significantly further downstream when the flow excited at 645Hz than for either of the other two cases.

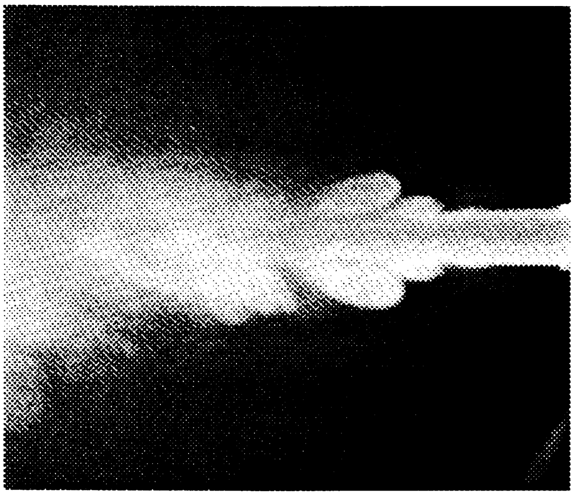

Figure 17. Unexcited Flow

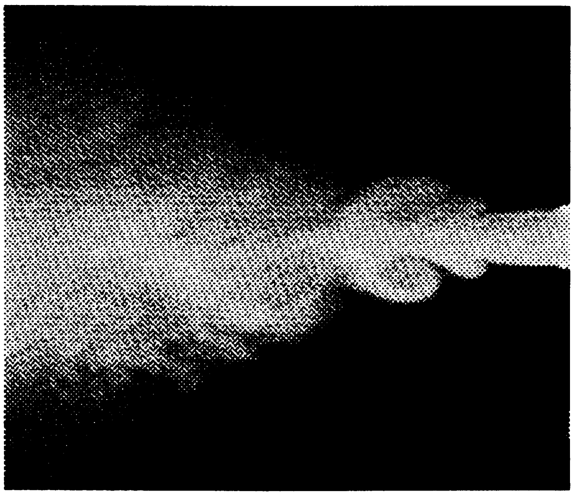

Figure 18. Piezo Excitation at 420Hz

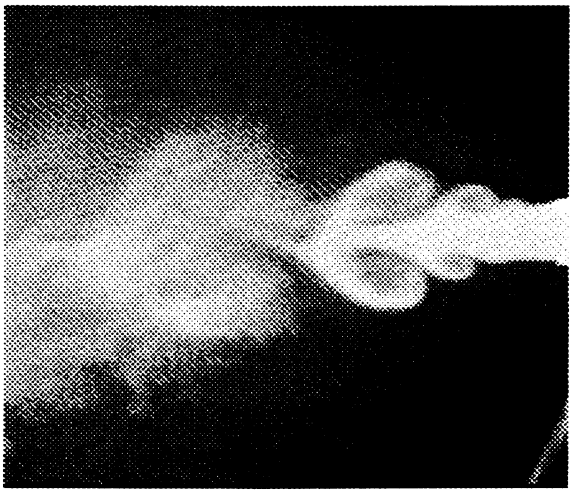

Figure 19. Piezo Excitation at 645Hz

CONCLUSIONS

The results indicate that a piezo actuator at the nozzle exit plane can modify the mixing layer development in a substantial manner. This form of excitation seems to be particularly useful for promoting the formation of vortices in the initial region of the jet and for controlling the frequency of these vortices.

When compared to global excitation of the flow, for example via acoustic excitation, piezoelectric actuation is able to provide a comparable level of flow modification but for a significantly lower power input. This represents a considerable advantage in those applications were power consumption is an important consideration.

The results confirm the suggestion of Lepicovsky (1989) viz. increasing the intensity of v' fluctuations in the mixing layer can have a large influence on the formation of mixing layer vortices.

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