Characteristics of Excited Shear Layers

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Numerical simulations of the two dimensional turbulent mixing layer subjected to controlled excitation leading to turbulence suppression are carried out using a vortex-in-cell method. Details of the flow characteristics, in terms of the contours of vorticity, stream function and Reynolds stress are presented and discussed. The results of an experimental study of an axisymmetric mixing layer subjected to high amplitudes of excitation are also presented. The experimental results support the numerical finding that at high amplitudes of excitation the maximum turbulence suppression occurs at a frequency higher than the maximally unstable frequency predicted by the linear theory.

Introduction

THE instability characteristics of shear layers have been extensively studied employing acoustic excitation. The mixing layers formed by merging of two streams initially separated by a thin surface are known to be dominated by quasi-two-dimensional structures that develop initially from the Kelvin-Helmholtz instability of a vortex sheet. One can manipulate the downstream development of a mixing layer using acoustic excitation. This possibility of modifying the evolution of large scale structures in the initial region of jets and mixing layers has attracted much attention because of its practical importance. From an application point of view two sets of excitation conditions can be identified: 1) excitation conditions resulting in the augmentation of turbulence intensities and 2) excitation conditions resulting in the reduction of turbulence intensities. For a recent review of the subject of perturbed mixing layers see Ref. 1. In the present paper, we are concerned with the reduction in turbulence intensities in the initial region of mixing layers due to controlled excitation.

The phenomenon of turbulence suppression (reduction in turbulence intensities) due to controlled excitation was first observed by Vlasov and Ginevskiy[2] and Petersen et al.[3] at certain frequencies of excitation. The first detailed study of turbulence suppression in free shear flows, however, was due to Zaman and Hussain.[4] They investigated the turbulence suppression due to controlled excitation in a number of experimental facilities circular jets, a plane jet and a single stream plane mixing layer. They observed: a) turbulence suppression only when the exit boundary layer was laminar and b) turbulence suppression in shear flows was maximum when the shear layer was forced at around the maximally unstable frequency, i.e., $St_\theta = 0.017$.[5] Here, $St_\theta (= f\theta_e/U_e)$ is the excitation Strouhal number, f is the forcing frequency, θ_e and U_e are the exit boundary layer momentum thickness and free-stream velocity, respectively. The experiments were carried out with amplitudes of excitation in the range of 0.3 to 1.0 percent of u_f'/U_e, u_f' and is the rms velocity at the frequency of excitation. From the flow visualization and conditional sampling studies, they surmised that forcing the shear layer at $St_\theta = 0.017$ produced the fastest growth and roll up of the shear layer, which resulted in early saturation and transition of structures and inhibited the formation of large vortices. As a consequence, the large fluctuation intensity otherwise caused by the passage and interactions of large vortices was reduced.

Zaman and Hussain[4] claimed that the maximum suppression obtained due to controlled excitation was as high as 80 percent. This claim was based on a point measurement at a specific spatial location of the flow. It should also be noted that the amplitude of excitation was in the range of 0.3 to 1.0 percent.

In an effort to further investigate and understand the phenomenon of turbulence suppression a numerical simulation of excited shear layers was undertaken by Nallasamy and Hussain.[6] The numerical simulation showed that at low amplitudes of excitation the maximum suppression occurs at a Strouhal number corresponding to the maximally unstable frequency consistent with the experimental observation. However, for high amplitudes of excitation the above Strouhal number preference is lost. That is, the maximum turbulence suppression no longer occurs at the maximally unstable frequency, but occurs at a higher frequency.

In this paper we present the results of further numerical and experimental investigations of the phenomenon of turbulence suppression. Details of the flow characteristics in terms of the contours of vorticity, stream function, and Reynolds stress obtained from the numerical simulation are presented. The recent experimental results of high amplitude excitation of an axisymmetric mixing layer are presented and discussed.

Numerical Simulation

Controlled excitation studies of jets and mixing layers suggest that the sensitivity of the normally turbulent flows to external forcing is related to the rotational inviscid behavior of these flows. Then the representation of turbulence as a superposition of interacting vortices appears to be a valid and useful idea. Several investigators have used the idea and simulated the mixing layers by a system of discrete vortices. Most discrete vortex methods fall in one of two categories: 1) the simulation of a spatially developing mixing layer as in a laboratory. In this method, vortices are shed one every time step such as at the end of a virtual splitter plate.[7,8] The strength of each vortex is determined by the velocity difference ΔU. The velocity of each vortex at any time step is calculated by directly summing the velocity field induced by individual vortices in addition to the contribution of the convection velocity. This method is very time consuming for a large number of vortices. 2) the simulation of a temporally developing mixing layer. Here, the mixing layer is replaced by a system of point vortices, distributed in a finite region under the periodic boundary condition, and the coordinate system moves with the convection velocity. The temporal development of the distribution of vortices is studied.[9,10] Use of the vortex-in-cell method results in less computing time than the direct sum-

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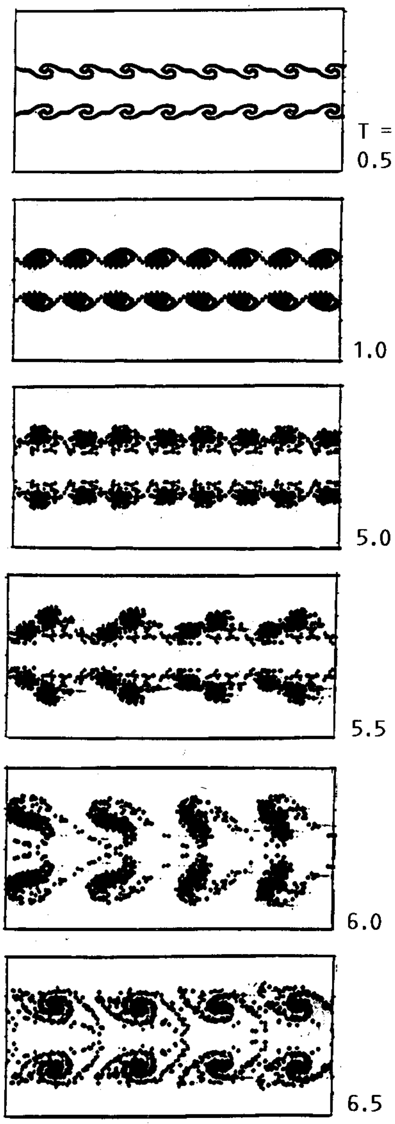


Fig. 1 Vortex roll-up and pairing in a plane jet subjected to symmetric disturbance.

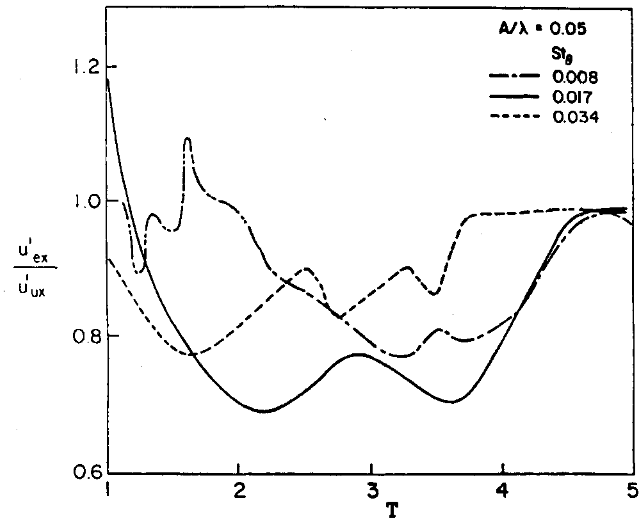


Fig. 2 Computed variation of turbulence suppression at low amplitude (A/λ = 0.05) of excitation: Effect of St_θ.

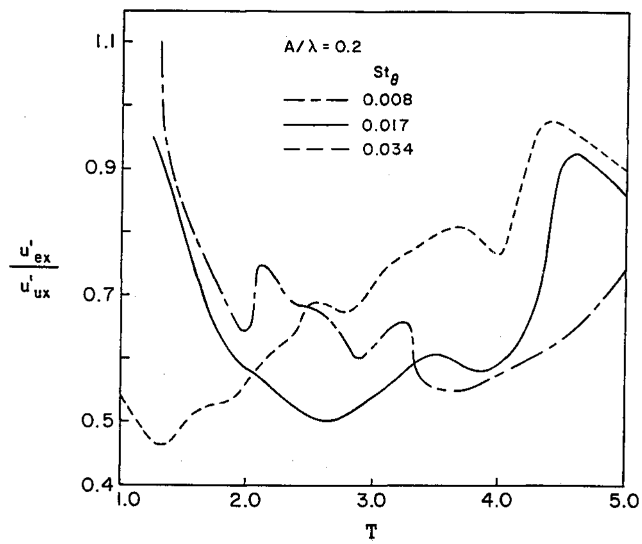


Fig. 3 Computed variation of turbulence suppression at high amplitude (A/λ = 0.2) of excitation: Effect of St_θ.

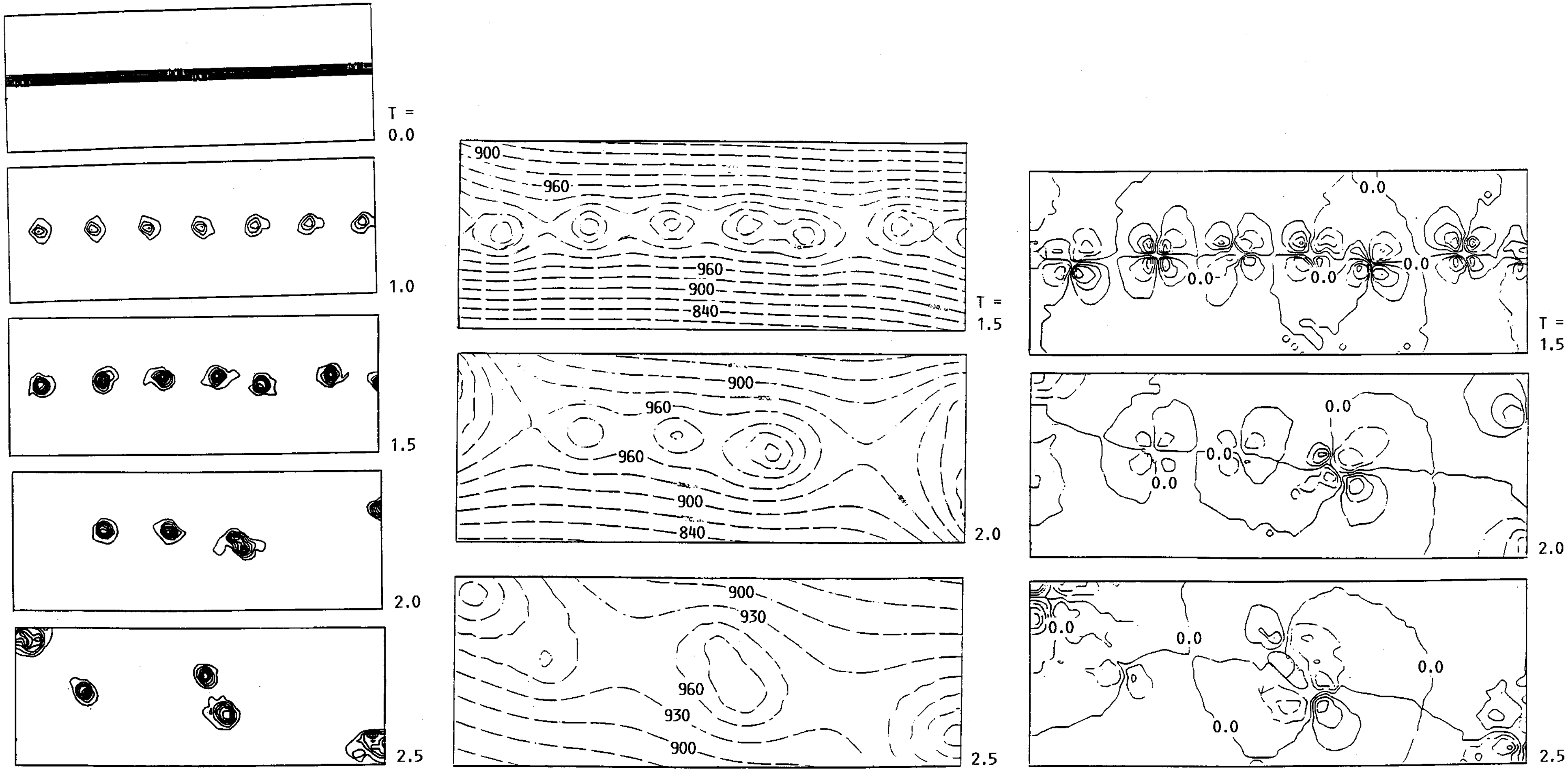
mation method. The advantage of the vortex-in-cell method is that the amount of computation is linear in N (the number of vortices), whereas in direct summation it is quadratic in N.

In the present paper, we study the temporal evolution of the shear layer employing the vortex-in-cell method. The details of the method are described in Ref. 6. We superimpose a 128 × 128 grid on the shear layer represented by 4096 point vortices, with periodic boundary condition in the x direction. The adequacy of the time stepping accuracy has been verified on both the evolution of the single shear layer and the evolution of two shear layers with symmetric sinusoidal disturbance (simulating the "puffing" instability of a plane jet). Although smoothing procedures[11] could be employed to extend the useful evolution time no such procedure was attempted in the present simulation. Figure 1 shows an example of the vortex roll-up and pairing in a plane jet subjected to a symmetric disturbance (the positions of the point vortices are shown). The computation can be carried out up to the second stage of pairing before the symmetry is broken due to numerical errors that result from the increased size of the vortex after mergers in relation to the width of the computational domain and time stepping. The detailed characteristics of an excited shear layer were examined at different frequencies and amplitudes of excitation. Contours of vorticity, stream function, velocity fluctuations and Reynolds stress were examined.

Experimental Investigation

The experimental study was carried out in a large axisymmetric mixing layer. An initially laminar mixing layer of a jet of diameter 27 cm was subjected to high amplitude excitation at each chosen frequency. A periodic disturbance of the given frequency and amplitude was applied through an axisymmetric slit at the jet lip.[12] The excitation was induced at the initiation of the shear layer without forcing the bulk of the flow. Data were taken using a miniature x-wire probe traversed by a computer. Velocity signals were digitized by an A/D converter at the rate of 51 kHz and then the mean and fluctuating components were computed. The rms values of the streamwise velocity fluctuations u_f were measured using a spectrum analyzer (Spectroscope SD 335). For the measurements reported in this paper, the initial boundary layer was laminar, the mean velocity profile agreeing with the Blasius profile.

The initial conditions (namely, the profiles of mean and fluctuating velocities) and the amplitude of excitation were measured at x/θ_c = 20. The frequency and the amplitude of excitation were varied at a constant exit velocity (U_e = 15 m/sec) of the jet. The exit boundary layer momentum thickness was 0.374 mm. Four amplitudes of excitation, namely, u_f'/U_e = 0.5, 2.5, 3.5, and 4.5 percent were considered. The frequency (St_θ) of excitation was varied from 0.006 to 0.25.

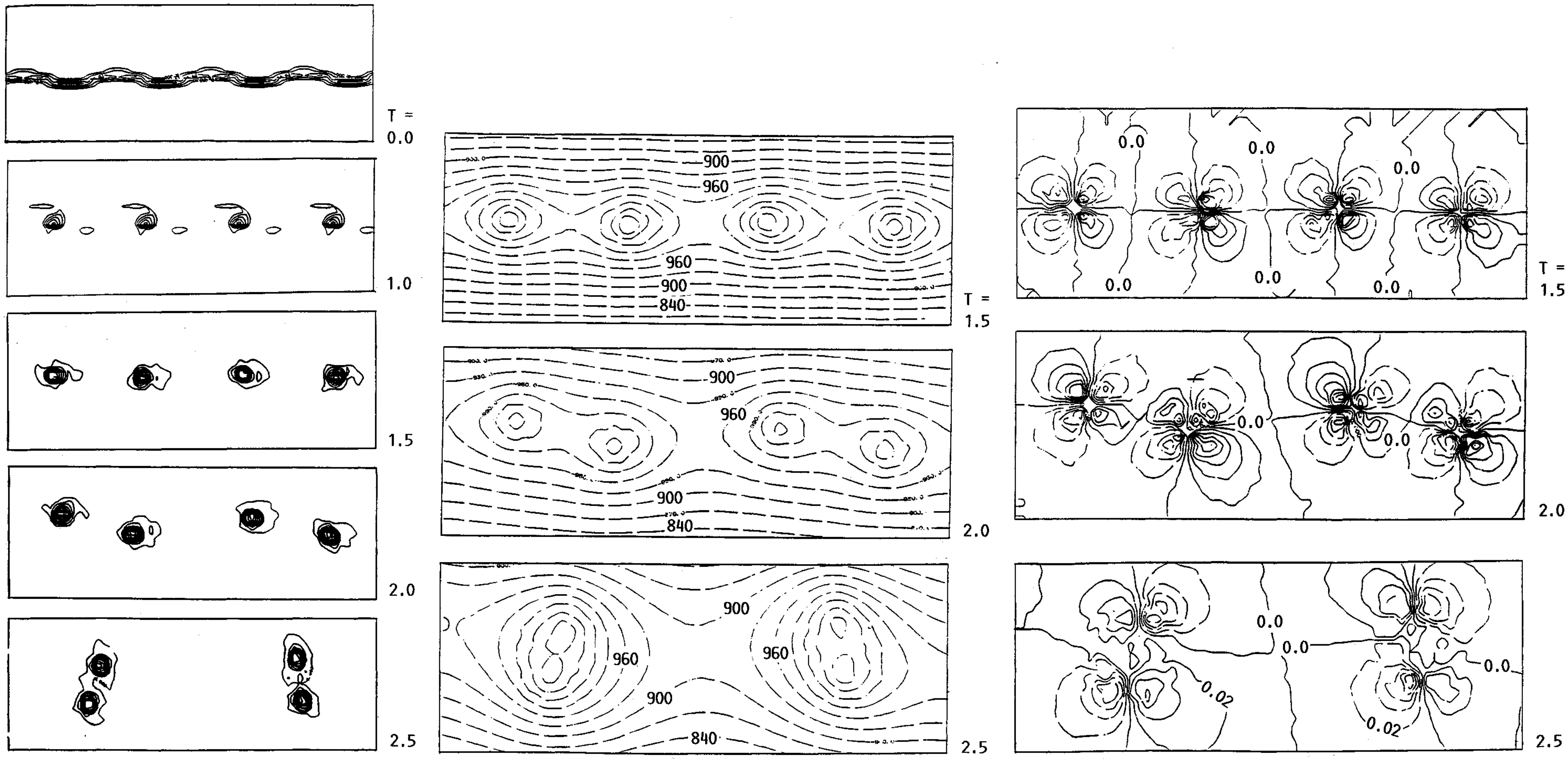


a) Vorticity contours

b) Stream function contours

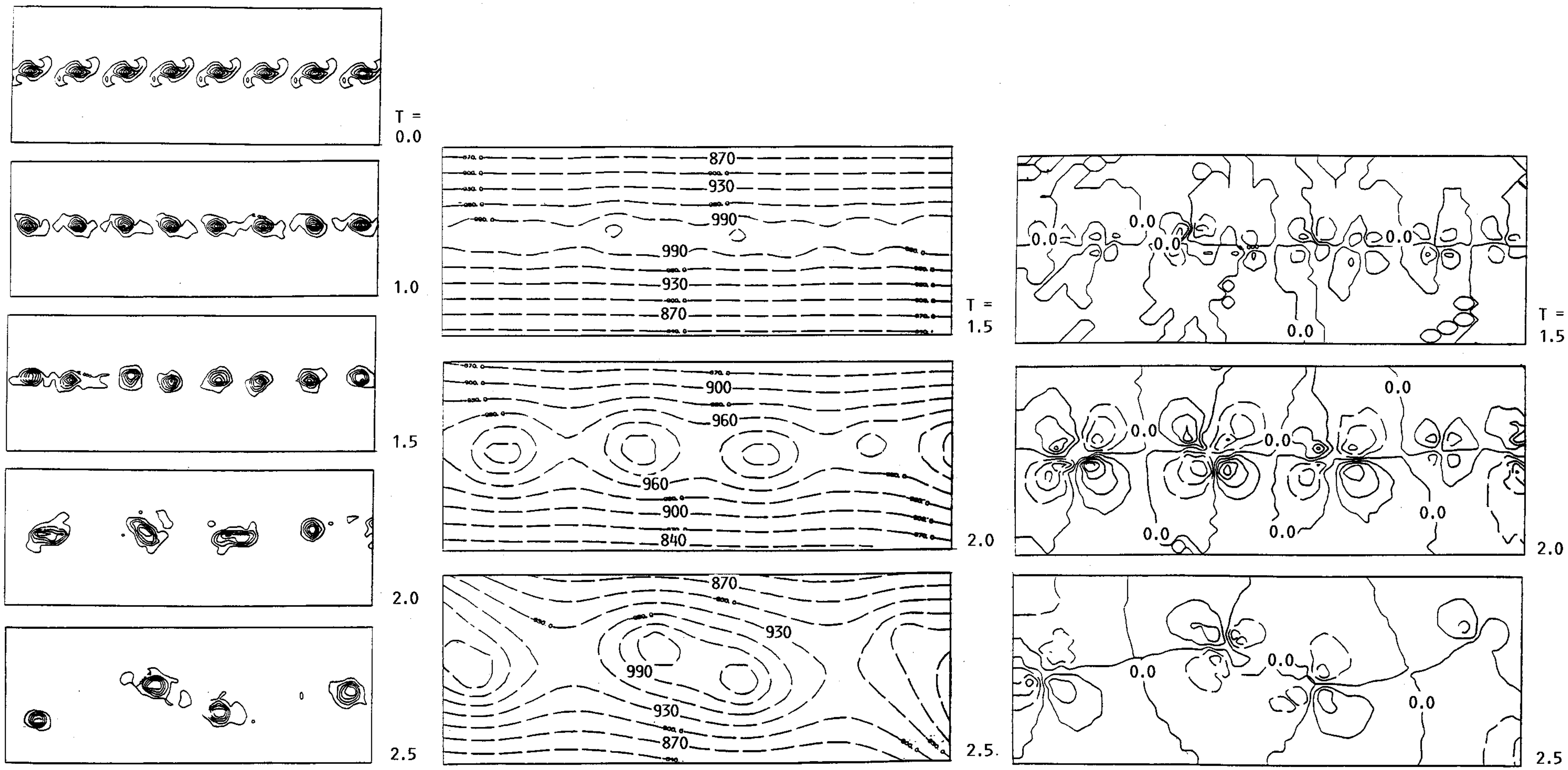
c) Reynolds stress contours

Fig. 4 Structure of unforced mixing layer.



a) Vorticity contours b) Stream function contours c) Reynolds stress contours

Fig. 5 Structure of the forced mixing layer at low amplitude (A/λ = 0.05) excitation, St_θ = 0.017.



a) Vorticity contours b) Stream function contours c) Reynolds stress contours

Fig. 6 Structure of forced mixing layer at high amplitude (A/λ = 0.2) excitation, St_θ = 0.034.

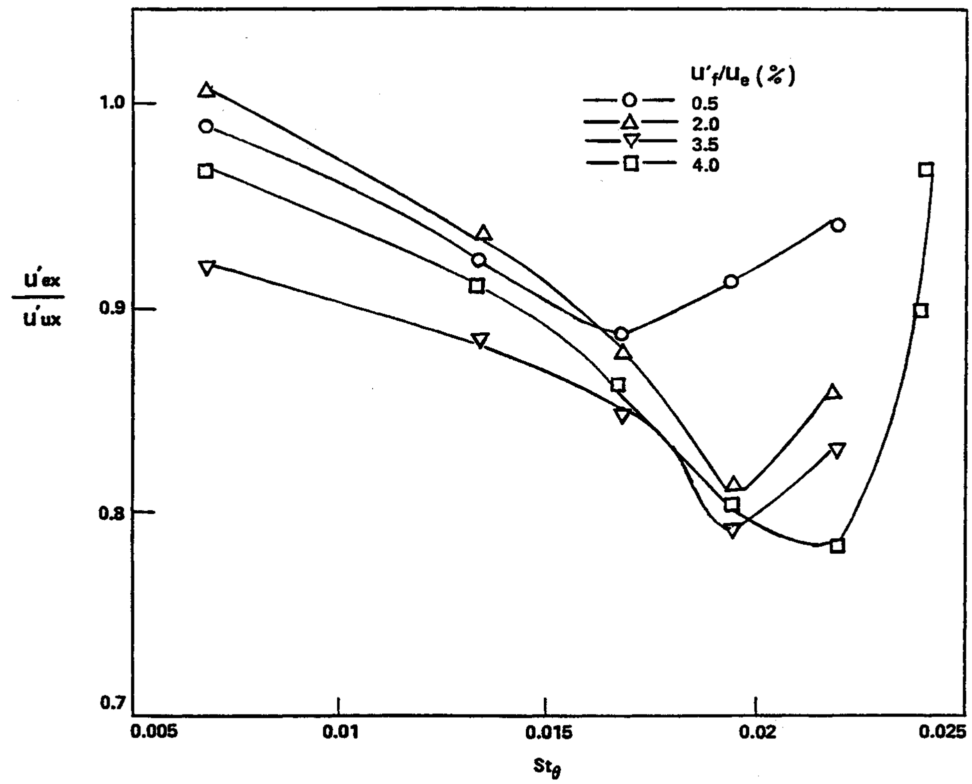


Fig. 7 Measured variation of turbulence suppression with forcing frequency: Effect of forcing amplitude.

Results and Discussion

Numerical Simulation

For a given set of initial conditions the temporal evolution of the shear layer is computed. At each time step of the simulation the position of the vortices and velocities on the grid points are known. The mean velocity u is obtained as x average

$$\bar{u}(y, t) = \int u(x, y, t)dx$$

The mean velocity $\bar{u}$ goes to a constant value $\Delta U/2$ well above the shear layer and $-\Delta U/2$ well below the shear layer. We compute the momentum thickness as

$$\theta(t) = \int (0.25 - (\bar{u}/\Delta U)^2)dy.$$

The momentum thickness is computed at every time step. At regular intervals the properties of coherent structures were examined. The time averaged profiles of turbulence intensity and Reynolds stress were computed. The typical interval for the time averages were such that the momentum thickness increases by about 5 percent. The ratio u'_{ex}/u'_{ux} of the peak longitudinal velocity fluctuation at a section with excitation, u'_{ex} to the peak longitudinal velocity without excitation, u'_{ux} is defined as the suppression factor. The excitation frequency St_θ in the numerical simulation is expressed as $St_\theta = 0.5\theta_i/\lambda$ where θ_i is the initial momentum thickness of the undisturbed shear layer and λ is the wavelength of the disturbance. In the simulation we vary the wavelength λ to obtain the desired frequency, St_θ of excitation. The amplitude of excitation is defined as A/λ where A is the amplitude of the sinusoidal disturbance and λ is the wavelength of the disturbance. Preliminary results of the numerical simulation were reported in Ref. 6. The main results of that paper will be first discussed for clarity.

We digress a little here to discuss the level of success of the numerical methods in predicting the turbulence intensities. In most simulations the absolute values of the velocity fluctuations are higher than those found in the experiments.[7,10,13] Ashurst's simulation[7] incorporated viscosity twice, using both the random walk and the viscous increase of the size (aging of the discrete vortices), in an effort to match the computed intensities to the experimental ones. With the viscous effects included, he could match only the longitudinal velocity fluctuations. Aref and Siggia[10] found that the velocity fluctuations in their large simulation (256 × 256 grid and 4096 vortices) were high compared to the experimental values. Also, the transverse velocity components were larger than the longitudinal ones though the reverse is true for the high Reynolds number flows of the simulation. Action[13] found that the simulation produced velocity fluctuations much higher than the measured ones, which is also true in the present simulations. Recently, Inoue,[8] in his simulation of the spatial evolution of the shear layer, similar to that of Ashurst's, but with a first order time integral scheme, obtained a correct ratio of the longitudinal to transverse velocity components though the absolute values of the individual components which were higher than the data by about 100 percent. Since in the present simulation, we are considering only the ratio of the longitudinal fluctuation intensities with and without forcing, it is believed that the trends of the results of turbulence suppression are correctly predicted.

The suppression factor u'_{ex}/u'_{ux} as a function of time is shown in Fig. 2 for three Strouhal numbers, for an excitation amplitude (A/λ) of 0.05. It is seen that the maximum turbulence suppression occurs for a Strouhal number of 0.017, the theoretical maximally unstable frequency. The suppressions for $St_\theta = 0.008$ and 0.034 are less pronounced. This is in agreement with the experimental results of Zaman and Hussain.[4] One aspect of the numerical simulation is that the curves are not smooth as in the measurements. A larger simulation (more rolled up vortices) and an ensemble average of large samples may produce a smooth variation of the suppression factor.[10]

Next, it is of interest to examine the effect of amplitude of excitation on the suppression factor. The results obtained for three Strouhal numbers for an excitation amplitude (A/λ) of 0.2 are shown in Fig. 3. It is seen that with this amplitude of excitation, the maximum turbulence suppression no longer occurs at $St_\theta = 0.017$, but occurs at a higher Strouhal number.

In an effort to understand the turbulence suppression, the coherent structure properties were examined. The contours of vorticity, stream function, and Reynolds stress were obtained for each of the cases considered. Here we present results for three cases: 1) unforced mixing layer (2) low amplitude, $A/\lambda = 0.05$, forced mixing layer at $St_\theta = 0.017$, and 3) high amplitude, $A/\lambda = 0.2$ forced mixing layer at $St_\theta = 0.034$. Figures 4(a)–4(c) show the vorticity, stream function and Reynolds stress contours, respectively, of the unforced mixing layer. The initial conditions for the unforced mixing layer include an extremely small random displacement of the position of point vortices, to enable ensemble average. This results in the observed non-uniformity in the initial vorticity distribution. The contours of vorticity and stream function at later times clearly depict the vortex roll up and pairing processes observed experimentally. For a low amplitude forcing at $St_\theta = 0.017$ (Fig. 5), the rate of roll up and pairing is increased. The coherent Reynolds stress contours at the corresponding time levels indicate the emergence of dominant regions of counter gradient transport, during pairing.

The contours of the large structures at a high amplitude ($A/\lambda = 0.2$) forcing are shown in Fig. 6. The vorticity contours show that when the amplitude of excitation is higher, the "debris" produced during the roll up and pairing are higher compared to that of low amplitude excitation. Changes in the rate of roll up and pairing and the extent of the regions of counter gradient transport can be observed. The process involved in the shifting of the frequency of maximum turbulence suppression from $St_\theta = 0.017$ at low amplitude excitation to a higher frequency at high amplitude of excitation is not clear and the quantitative estimate of the changes is difficult.

The results of the experimental investigation described below, however, supports the high amplitude forcing results of the numerical simulation. A high initial amplitude together with the fast transition for frequencies larger than the maximally unstable frequency seem to produce a higher suppression.

Experiments

As in the numerical simulations, the suppression factor is calculated as the ratio of maximum longitudinal velocity fluctuation at a section with excitation u'_{ex} to that without excitation u'_{ux} at the same section. In the experiment, the frequency of excitation is varied at constant values of the jet exit velocity U_e and the momentum thickness θ_e. The amplitude of excitation is expressed as u'_f/U_e where u'_f is the rms value of the longitudinal fluctuation at the frequency of excitation. The variation of the suppression factor with the amplitude of excitation is shown in Fig. 7. The figure shows suppression factor at a distance $x/\theta_e = 200$ where the turbulence suppression was found to be the maximum. (The maximum turbulence suppression was found to occur at the same downstream distance of 200 θ_e for all Strouhal members considered.) We see that at an amplitude of 0.05 percent the maximum suppression occurs at the maximally unstable frequency predicted by the linear theory, $St_\theta = 0.017$, as in the experiments of Zaman and Hussain.[4] However, the magnitude of the maximum suppression in the present study is only about 12% in contrast to 80% in their study. This difference in magnitudes stems from the definition of suppression factor. They define suppression factor as the ratio of longitudinal velocity fluctuations at a point with and without excitation. The suppression of 80% was found at a point $x = 10$ cm in the jet and $y = 0.5D - 1.27$ cm (D is the diameter of the jet). Such a definition of the suppression factor based on the intensities at a single point may not adequately characterize the turbulence in the near field for the following reasons: when a shear layer is acoustically excited, the vortical structures are displaced in radial, axial directions, pairing of vortical structures is induced, the location of the vortex pairing is changed, etc. It is thus possible that the intensities at a point with and without structure are quite different. The suppression factor defined on the basis of peak intensities at any section with and without excitation as in the present (numerical and experimental) study better represents the turbulence suppression. Reverting to Fig. 7, with the increase in the amplitude of excitation to 2% the maximum suppression occurs at a higher Strouhal number of 0.0194. For an amplitude of 3.5%, the maximum suppression still occurs at $St_\theta = 0.0194$. With a further increase in the amplitude of excitation to 4.5%, the maximum suppression shifts to $St_\theta = 0.022$. Thus, we see that

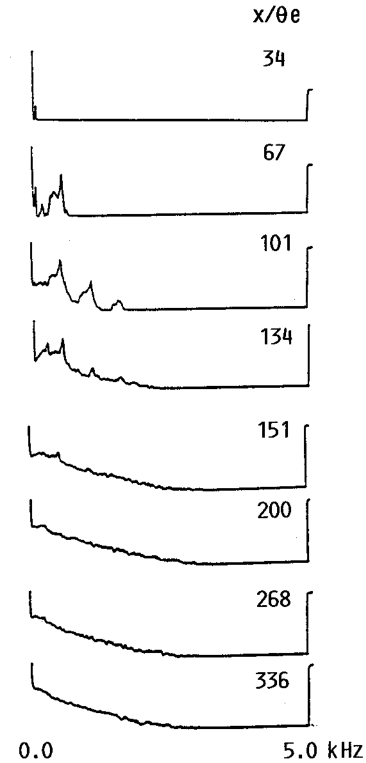


Fig. 8 Measured longitudinal velocity spectra along the line $U/U_e = 0.7$, $St_\theta = 0$.

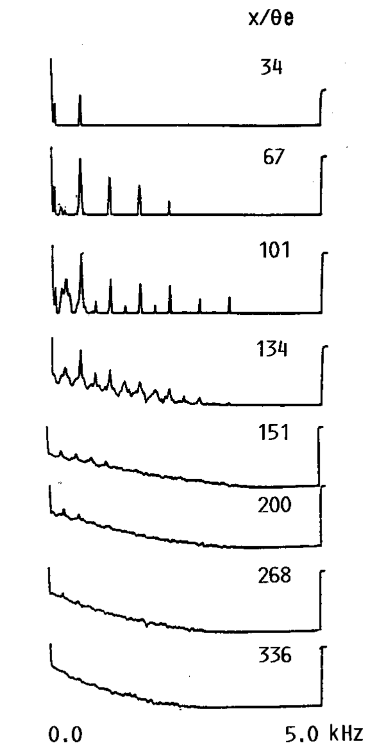


Fig. 9 Measured longitudinal velocity spectra along the line $U/U_e = 0.7$, $St_\theta = 0.017$, $u'_f/U_e = 0.5\%$.

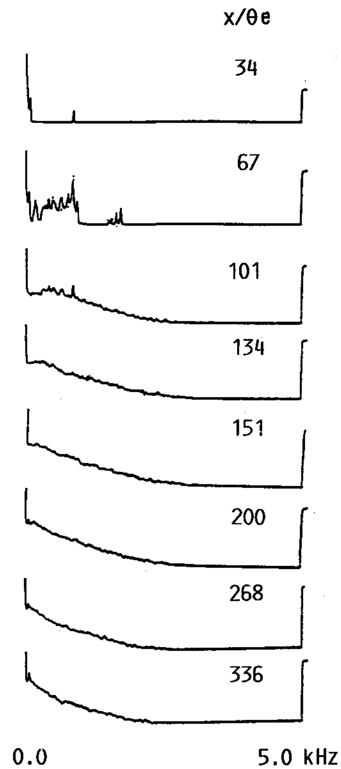


Fig. 10 Measured longitudinal velocity spectra along the line U/U_e = 0.7, St_θ = 0.022, u_f'/U_e = 4.5%.

the maximum turbulence suppression shifts to higher Strouhal numbers as the amplitude of excitation is increased, in the range of amplitudes studied. This confirms the observations of numerical simulation at high amplitudes.

An examination of the longitudinal velocity spectrum at different x along the straight line corresponding to U/U_e = 0.7 showed that a higher amplitude forcing can hasten transition to turbulence only when the excitation frequency is greater than the maximally unstable frequency. The transition was taken to be complete when the peaks in the spectrum disappear and resembles that of a fully turbulent flow.[14] Typical spectra obtained at no forcing $St_\theta = 0$, 0.5% amplitude forcing at $St_\theta = 0.017$ and 4.5% forcing at $St_\theta = 0.022$ are shown in Figs. 8–10. High amplitude forcing at frequencies greater than the maximally unstable frequency is seen to result in earlier saturation, lower level of saturation, and faster transition to turbulence. These nonlinear interactions seem to be responsible for the observed turbulence suppression at high amplitudes of excitation. It appears that the nonlinear interactions in the turbulence suppression can not be explained by employing a simple extension to the linear theory.[15]

Concluding Remarks

Numerical simulations of the two-dimensional turbulent mixing layers subjected to controlled excitation leading to turbulence suppression were carried out using a vortex-in-cell method. For low amplitudes of excitation, the maximum turbulence suppression occurs at the maximally unstable frequency, $St_\theta = 0.017$. At high amplitudes of excitation the maximum turbulence suppression occurs at a frequency higher than the maximally unstable frequency.

An examination of the details of the large scale structure properties show the dependence of the roll up, rate of pairing, and the emergence of regions of counter-gradient transport on the forcing frequency.

The results of the experimental study of an axisymmetric mixing layer subjected to controlled acoustic excitation were presented. The results show that at low amplitudes of excitation the maximum turbulence suppression occurs at St_θ = 0.017, as in the previous study.[4] At high amplitudes of excitation, the maximum turbulence suppression occurs at a frequency higher than the maximally unstable frequency, depending on the amplitude of excitation, as in the present numerical simulation.

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