Vortex Simulation of Forced/Unforced Mixing Layers

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Abstract

TWO-DIMENSIONAL, spatially growing, turbulent mixing layers are simulated numerically by a vortex method and the results are compared with those determined experimentally. The effects of artificial forcing on flow development are also studied. The profiles of statistics for unforced mixing layers show similarity, and their peak values are in good agreement with experimental values except for rms v'. Results for forced mixing layers show that mixing layer growth is enhanced for low-frequency forcing, whereas it is suppressed for high-frequency forcing and that good agreement with experimental peak v' is now obtained. Many of the flow features observed experimentally are reproduced. The applicability of a two-dimensional vortex method for forced/unforced mixing layers is discussed.

Contents

One of the goals of this study is to add new data to the knowledge concerning the applicability of a two-dimensional (2D) vortex method to simulate forced/unforced mixing layers and to increase the understanding of a turbulent mixing layer. The numerical method used is an adaptation of that used by Inoue.[1] Two major modifications were made: 1) the effect of walls is taken into consideration because many of the experiments have been performed in wind tunnels and 2) vortices are deleted from the computation when they are sufficiently far downstream from the test section in which reliable results are expected. This treatment allows a calculation to be made for a period long enough to measure the statistics. In cases where forcing is applied, each new vortex appearing at the end of splitter plate is assigned the normal velocity component v_f of the form, $v_f(t) = A \sin(2\pi f t)$, in addition to the velocity induced by individual vortices. Here t is the time. The simulation parameters were prescribed as follows: velocity ratio $r \equiv U_2/U_1 = 0.3$, 0.46, and 0.6; forcing frequency $f = 0.0$, $0.25F$, $0.5F$, and $2F$; and forcing amplitude $A = 0.0$, $0.01U_c$, $0.1U_c$, $0.5U_c$, and U_c. The symbols U_1, $U_2 (U_1 > U_2)$ are the freestream velocities and U_c $(= (U_1 + U_2)/2)$ the convection velocity. The predominant frequency F of the unforced mixing layer was determined from the relation,[2] $F\theta_i/(U_1 + U_2) \approx 0.02$. The dependence of the momentum thickness θ on the forcing frequency is presented in Fig. 1 for $r = 0.6$. An unforced mixing layer grows linearly with x after a short initial transient. The momentum thickness near the start of linear growth of the unforced mixing layer was chosen as the initial momentum thickness θ_i.

Time-averaged profiles of fluctuation velocities and the Reynolds stress of an unforced mixing layer are presented in Fig. 2 for $r = 0.6$. The velocities are made dimensionless by $\Delta U (= U_1 - U_2)$. The coordinate η is defined as $(y - y_{0.5})/\theta$, where $y_{0.5}$ denotes the y position at which $U = U_2 + 0.5\Delta U$. In the figures, for comparison, the similarity profiles experimentally obtained by Oster and Wygnanski[2] for the same velocity ratio are represented by the solid lines. The Reynolds number of the experiment was about 10^4. Some features of the calculated results differ from those of the experiment. First, the peak value of rms u' is smaller than that of rms v', while experimental results show rms $u' >$ rms v'. The calculated peak value of rms u' compares reasonably well with the experimental one, but the calculated peak value of rms v' is about twice as high as is the experimetnal value. Second, the profile of rms u' is deformed in shape if it is compared with the profile obtained experimentally.

As seen from Fig. 1, for a low forced frequency ($f = 0.5F$), the growth rate of the mixing layer is higher than the unforced mixing layers for $0 < x < 80$ (hereafter, this region is referred to as region I). With increasing downstream distance, $80 < x < 160$, the growth of the mixing layer slows down (region II). Farther downstram $160 < x$, the mixing layer recovers its growth with increasing x (region III). Profiles of statistics in a low-frequency forced mixing layer ($f < F$) are shown in Fig. 3 for $f = 0.5F$. In the figures, the solid line indicates the similarity profile of the corresponding unforced mixing layer. Figure 3a shows that the profiles of rms u' are double-peaked in region II. Figure 3c shows that $-\overline{u'v'}$ becomes negative across the mixing layer in region II, indicating the occurrence of contragradient diffusion. These calculated features of low-frequency forced mixing layers are in excellent qualitative agreement with the experimental observation by Oster and Wygnanski.[2] They also found that the length of region II is given by $1 \le \lambda f x/U_c \le 2$, where λ is defined as $\lambda = (U_1 - U_2)/(U_1 + U_2)$. This criterion for the length of region II was satisfied in this study. Quantitative comparison of statistics was difficult because of the difference of forcing methods. (In the experiment, the forcing amplitude is given by the length over which an oscillating flap moves, whereas in the calculation it is given by velocity.) However, for a few quantities that are independent of both forcing frequency and amplitude, good quantitative agreement was also obtained. For example, Oster and Wygnanski found that in region II the maximum value of rms u' is approximately 0.15 in the lower-speed region of the double-peaked profile, irrespective of both velocity ratio and forcing frequency. The calculated result in Fig. 3a also shows the approximate maximum value of 0.15, independent of forcing amplitude. The calculated peak value of rms v' in

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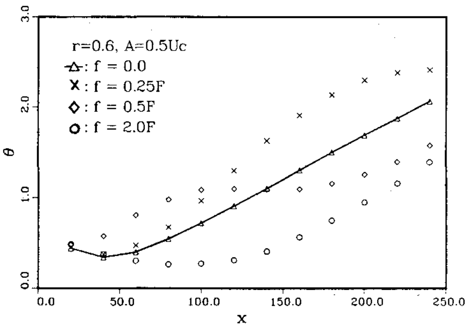

Fig. 1 Effect of forcing frequency on the momentum thickness, $r = 0.6$, $A = 0.5U_c$.

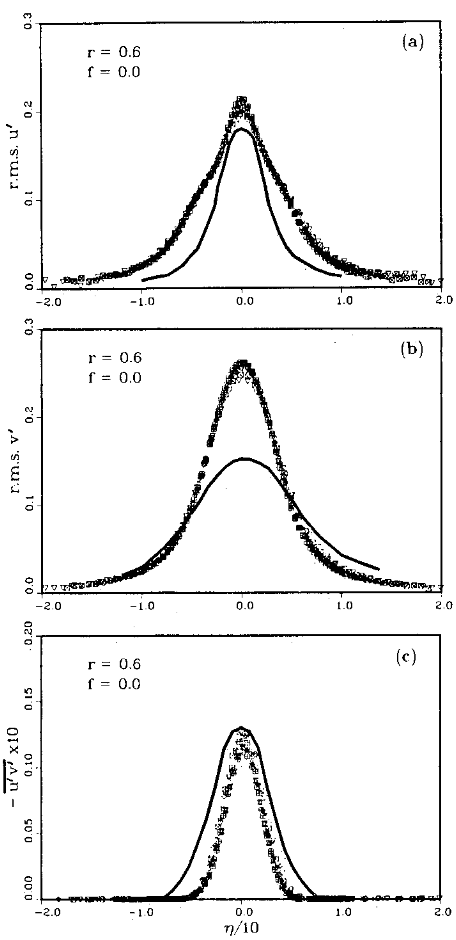

Fig. 2 Profiles of statistics in an unforced mixing layer, $r = 0.6$ (—— Oster and Wygnanski,[2] + $x = 60$, × $x = 80$, ◇ $x = 100$, ▽ $x = 120$, □ $x = 140$, ∗ $x = 160$, ◇ $x = 180$, ⊕ $x = 200$, XX $x = 220$, □ $x = 240$): a) rms u', b) rms v', c) $-u'v'$.

Fig. 3b is about 0.3 and this value does not significantly depend on A. The peak value of rms v' measured by Oster and Wygnanski was also about 0.3 for the same velocity ratio, $r = 0.6$. Remember that the difference of the rms v' of unforced mixing layers between the calculation and the experiment was about a factor of two. Oster and Wygnanski observed that, when 2D forcing is applied, the spanwise fluctuation (rms w') decreases and thus the flow becomes closer to 2D. In an experiment of a mixing layer at low Reynolds number, Browand and Weidman[7] observed rms $u' <$ rms v' and also a defomed profile of rms u'. In low Reynolds number flows, the small-scale streamwise vortices superimposed on large-scale spanwise vortices in high Reynolds number flows may be absent or at least weakened by viscosity; thus, low Reynolds number mixing layers should be more 2D. Thus, the 2D computational result rms $u' <$ rms v' and the deformed profile of rms u', both of which are contradictory to experimental results at high Reynolds numbers,

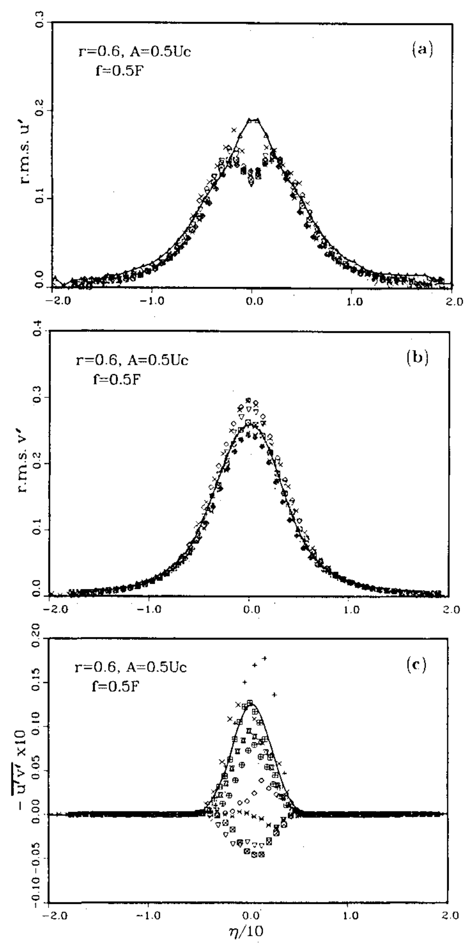

Fig. 3 Proflies of statistics in a low-frequency forced mixing layer, $r = 0.6$, $A = 0.5U_c$, $f = 0.5F$ (—— unforced, for symbols, see Fig. 2): a) rms u' in region II, b) rms v' in region II, c) $-u'v'$.

may be improved when the three-dimensional effects can be accounted for in the numerical simulations.

As seen in Fig. 1, for a high-frequency forced case ($f = 2F$), the growth rate of momentum thickness is much lower than the growth rate of the unforced mixing layer in the region $x < 120$. Profiles show that both rms u' and rms v' are smaller than the values of the unforced mixing layer in the region where growth of the mixing layer is suppressed. The plots of discrete vortex show that suppression of mixing layer growth is closely related to the inhibition of vortex pairing. These results are consistent with experimental observations.

This study suggests that 2D vortex method is quite effective and useful in simulating two-dimensionally forced turbulent mixing layers. On the other hand, the effect of three-dimensionality should be taken into account to simulate unforced mixing layers.

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