Near-field development of a turbulent mixing layer periodically forced by a bimorph PVDF film actuator

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Abstract

We have performed experiments in a turbulent mixing layer with periodic forcing introduced by a Piezo Film Actuator (PFA). Three different lengths of PFAs have been used, and the effects of various combinations of forcing amplitudes and frequencies are investigated. The forcing at the first and second sub-harmonic frequencies against the natural frequency enhances the development of the thickness of the mixing layer: the mixing layer spreads due to the forcing. On the other hand, the forcing near the natural frequency suppresses the development: the mean velocity gradient becomes steeper than the no control case. The vector pattern of the periodic velocity components indicated the formation of the vortical structure. By forcing at the natural and its first sub-harmonic frequencies, two counter-rotating vortices are clearly observed in one period of forcing. By forcing at second sub-harmonic frequency, the vortical structure is found only in the downstream region. The distribution of the periodic Reynolds shear stress significantly varies with the forcing frequency and it takes a positive value when forcing occurs near the natural frequency. However, the total value of the Reynolds shear stress remains negative due to the contribution of the turbulent components.

Key words: periodic forcing, turbulent mixing layer, piezo film actuator

1. Introduction

The mechanism of vortex dynamics has been studied extensively in various turbulent shear flows since Brown and Roshko performed a visualization of the quasi-coherent vortical structure in turbulent mixing layers. Such vortex structures are generated by the Kelvin-Helmholtz instability, and its unstable mode can be calculated using the linear stability analysis. The detailed mechanism of the interaction of coherent vortices is revealed by direct numerical simulation (DNS) of the temporally and spatially developing turbulent mixing layers. On the other hand, in experiments, it is known that the development of the mixing layer is “super-sensitive” to the initial conditions. The development of vortices is affected by perturbations introduced at the inlet, which is often “facility-dependent”: the inlet boundary layers being laminar or turbulent, and the two dimensional perturbation imposed by the splitter plate wake. Bell and Mehta performed an experiment of a two-stream mixing layer formed by tripped and untripped boundary layers, and reported that the spatial development of the statistics depends on the characteristics of inlet boundary layers. In the development of the mixing layer, a pair of vortices coalesce to form a single vortex, which is called pairing. Huang and Ho performed an experiment involving a mixing layer formed by laminar boundary layers with perturbations, and small scale turbulence was created after the merging of spanwise vortices by the interaction of spanwise and streamwise structures. Morris and Foss investigated the developing region of a single-stream shear layer separated from a fully

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1
developed turbulent boundary layer. They reported that the dynamics of the vortical structure plays an important role in determining the development of the statistics.

By making use of the high-sensitivity to the initial conditions of the mixing layer, many attempts have been made to control their development by introducing periodic forcing. The development of the vorticity and momentum thicknesses can either be enhanced or suppressed by choosing certain forcing conditions, i.e., amplitude and frequency. Ho and Huang\textsuperscript{(10)} performed an experiment with forcing at various frequencies, and they reported that the vortex pairing is enhanced when the forcing frequency is sub-harmonic with respect to the natural frequency. Husain and Hussain\textsuperscript{(11)} performed an experiment in a perturbed jet with two frequencies: one being the half of the other. The streamwise location of the pairing can be controlled by changing the phase-lag between two control inputs. Suzuki et al.\textsuperscript{(12)} conducted an experiment using an axisymmetric jet nozzle with 18 miniature electromagnetic flap actuators at its exit. In their experiment, various modes of vortex structure are achieved by changing the Strouhal number. Oster and Wignanski\textsuperscript{(13)} and Weisbrot and Wignanski\textsuperscript{(14)} performed a series of experiments using the forcing frequency one order lower than the natural frequency. The forced mixing layer exhibits a region where its thickness does not grow in the streamwise direction. This is caused by the quasi two-dimensional vortex lumps, which do not interact with one another. Due to the slight inclination of these vortices, the sign of the Reynolds shear stress becomes opposite to that anticipated from the mean shear direction. This Reynolds shear stress contributes to the suppression of the development of the momentum thickness. On the other hand, a series of experiments with forcing significantly higher than the natural frequency were attempted\textsuperscript{(15)–(17)}. They intended to increase the dissipation directly and enhance the small scale mixing. They reported that the very high frequency actuation is locally effective, and it dramatically increases the small-scale scalar mixing when it is combined with low frequency forcing.

In the present study, we performed the velocity measurements in the early developing region of the mixing layer. The development of the mixing layer thickness is evaluated, and the mechanism of their enhancement and suppression due to the periodic forcing with different amplitude and frequencies is discussed. The inlet boundary layers are tripped and fully developed turbulent boundary layers are established before they merge. The periodic forcing with three different frequencies is imposed at the tip of the splitter plate: approximately the same as natural frequency, its first and second sub-harmonic frequencies. The development of the thickness and velocity statistics is examined. In addition, we particularly focus on the interaction of the periodic and the turbulent components, and its relationship with the vortical structure.
Table 1  Inlet conditions of the mixing layer at $x = 0.5$ mm.

<table>
<thead>
<tr>
<th></th>
<th>Free stream velocity: $U$ [m/s]</th>
<th>Free stream turbulence: $Tu_f$ [%]</th>
<th>Momentum thickness: $\theta$ [mm]</th>
<th>Reynolds number: $Re_\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>high speed side</td>
<td>6.8</td>
<td>0.86</td>
<td>0.88</td>
<td>398</td>
</tr>
<tr>
<td>low speed side</td>
<td>3.3</td>
<td>1.03</td>
<td>1.41</td>
<td>330</td>
</tr>
</tbody>
</table>

2. Experiments

2.1. Piezo Film Actuator (PFA)

We fabricated Piezo Film Actuators (PFAs), and used them to introduce a periodic excitation to the mixing layer. The PFA was comprised of two silver coated PolyVinylidene DiFluoride (PVDF) films with a thickness of $110 \mu m$ (3-1004346-0, Measurement Specialties Inc.). Two PVDF films were glued together with an adhesive and a conductive-double-sided tape so that a bimorph structure was created: the tape was used for the part sandwiched with two polycarbonate plates with a thickness of 0.5 mm and a width of 500 mm. These polycarbonate plates were fixed on the top and bottom of the splitter plate so that the PFA was attached to the splitter plate as shown in Fig. 1. The widths of the side gaps between the PFA and the polycarbonate plate were 5 mm. Three PFAs with different lengths of the protruding part, $L = 40$ mm, 27 mm and 20 mm, were created. The PFA was driven by sine-wave signals generated by a function generator (Function Synthesizer 1915, NF) and the signals were magnified by the amplifier (HOPP-1B3, Matsusada Precision Inc.). The resultant maximum operating amplitude was $\pm 1$ kV.

2.2. Flow and measurement apparatus

A blowing wind tunnel specially designed for the turbulent mixing layer\cite{18} was employed in the present study. Two free streams with different velocities, $U_h = 6.8$ m/s and $U_l = 3.3$ m/s, respectively, merged at the nozzle exit with a 0.5 × 0.5 m$^2$ section. These free stream velocities gave the velocity ratio, $r = U_l/U_h = 0.49$, the velocity difference $U_s = U_h - U_l = 3.5$ m/s, and the convection velocity $U_c = (U_h + U_l)/2 = 5.1$ m/s. Tripping wires were put on both sides at 150 mm upstream from the edge of the splitter plate and their diameters were 0.5 mm and 1 mm on higher and lower sides, respectively. The inlet boundary layers exhibited typical characteristics of the turbulent boundary layer. Table 1 summarizes the conditions of the inlet boundary layers.

We set the test section as shown in Fig. 2. The Cartesian coordinates (the streamwise direction $x$, the transverse direction $y$, and the spanwise direction $z$) were defined at the center of the tip of the PFA. The hotwire sensor was traversed in the transverse direction by a motorized slider, which was controlled by a PC, and traversed in the streamwise direction using a precise slider with a ball screw.
We used an X-type hot-wire probe (55P64, Dantec) operated by CTAs (1101, KANOMAX).

For the yaw-angle calibration of the X-probe, we used the look-up table technique\(^\text{(19)}\) with the velocity range from 2 to 6.8 m/s and the angle range from \(-42^\circ\) to \(+42^\circ\). The calibration was undertaken before and after every run of the experiment. Samples falling out of the range of the look-up table were compensated by the effective angle technique\(^\text{(20)}\), though such samples occupied approximately 2% of the total sample pool. Signals were low-pass filtered by an analog low pass filter (DT-5FL, NF) and converted to digital data by a data acquisition board (PCI-6030E, NI) equipped on a PC. The sampling rate was set to 10 kHz and the sampling time was 30 seconds at each measurement location. The vibration of the PFAs was measured by a laser displacement sensor (LK-G150, Keyence). We used Labview\(^R\) for controlling measurement procedures, and Matlab\(^R\) for the data processing.

### 3. Results

#### 3.1. Characteristics of PFAs

The frequency response of the PFAs is checked prior to the flow measurement. The resonance frequency \(f_r\) can be estimated by the formula for the vibration of a cantilever beam:

\[
    f_r = \frac{\lambda_n^2}{2\pi L^2} \sqrt{\frac{EI}{\rho w h}},
\]

where \(\lambda_n\) (\(=1.875\)) is the coefficient of the vibration mode, \(L\) is the length of the PFA, \(E\) (=2–4\(\times\)10\(^9\) N/m\(^2\)) is Young’s modulus of the piezo film, \(I\) is the geometric moment of inertia, \(\rho\) (=1780 kg/m\(^3\)) is the density of the piezo film, and \(w\) and \(h\) are the width and the thickness of the PFA, respectively. We prepared three PFAs with different lengths: 40 mm, 27 mm and 20 mm corresponding to the different expected resonance frequencies. Using Eq. (1), \(f_r\) becomes 24–33 Hz for \(L = 40\) mm, 52–73 Hz for \(L = 27\) mm, and 94–133 Hz for \(L = 20\) mm. It is noted that the estimated resonance frequency has a certain range due to the possible variation range of Young’s modulus, and we do not consider the effect of the adhesive. Hereafter, we refer to PFAs with length \(L = 40\) mm, 27 mm, and 20 mm as PFA-1, PFA-2 and PFA-3. The measured frequency response of the amplitude ratio and the phase delay of PFAs is shown in Fig. 3. The measurements were done in stationary air. PFA-1, 2, and 3 show their resonance frequency at 28 Hz, 62 Hz and 136 Hz with the maximum amplitude of 4.3 mm, 1.9 mm and 0.9 mm, respectively. In addition, the gradual phase-lag of the vibration against the input signal is observed. When the PFAs are placed in the flow, in the present case, the amplitude decreases to approximately half.

We set the control frequency \(f_c\) = 30 Hz, 60 Hz and 140 Hz for PFA-1, 2 and 3 so as to operate them near the resonance frequencies. We also changed the amplitude of the PFA by...
changing the input voltage. The combinations of the frequencies and the amplitudes tested in the present study are shown in Section 3.3. The amplitude of the input voltage was adjusted before each run of the experiment so that the amplitude of the PFA was set to the target value.

### 3.2. Base Flow

First, we looked at the development of the mixing layer without forcing. Measurements have been performed at the center of the PFA ($z = 0$), and five streamwise locations from $x = 25$ mm to 200 mm. In the transverse direction, $y$, the hotwire sensor was traversed every 0.9 mm near the center and every 1.8 mm in the outer part of the mixing layer. The velocity statistics are normalized by the velocity difference of the two free streams, i.e., $U^* = (U - U_l)/U_s$. We evaluate the development of the mixing layer in terms of the vorticity thickness. The vorticity thickness is defined as:

$$\delta_\omega = \frac{U_h - U_l}{\partial U/\partial y}_{\text{max}}.$$  

The vorticity thicknesses $\delta_\omega$ measured at the most upstream location ($x = 25$ mm) are 5.18 mm, 5.20 mm and 7.06 mm for the PFA-1, -2 and -3. The momentum thickness may be calculated from the hyperbolic tangent mean velocity profile fit to the measured data so that the effect of the splitter plate wake can be avoided.

$$U^*_{\text{hyp}} = 0.5 \tanh(cy) + 0.5,$$  

where $c$ is determined so that the hyperbolic tangent velocity profile has the same maximum velocity gradient as the measured data. The solid lines in Fig. 4 indicate such velocity profiles.
Table 2  Conditions of forcing.

<table>
<thead>
<tr>
<th>case</th>
<th>(L) [mm]</th>
<th>(f_c) [Hz]</th>
<th>(A) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF A1 NC</td>
<td>40</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>(f30A0.5)</td>
<td>0.5</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>(f30A2)</td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>PF A2 NC</td>
<td>27</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>(f60A0.5)</td>
<td>0.5</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>(f60A1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PF A3 NC</td>
<td>20</td>
<td>140</td>
<td>0</td>
</tr>
<tr>
<td>(f140A0.5)</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

calculated by Eq. (3).

In Fig. 4, the comparison of the mean velocity distributions of cases without forcing but with different PFAs installed is given; the results at different streamwise positions are presented. The axes are normalized by the local vorticity thickness \(\delta_\omega\) and the origin of the transverse axis is adjusted according to the local \(y_{0.5}\) position where the dimensionless mean velocity takes the value of 0.5, i.e., \((U(y_{0.5}) - U_l)/U_s = 0.5\). The mean velocity profiles show good agreement although minor differences are observed near the higher velocity side at the most upstream location. The velocity deficit observed in the upstream region gradually decreases in the downstream direction until it finally disappears. The measured mean velocity profiles agree well with the hyperbolic tangent velocity profile at the location farthest downstream.

The power spectra of transverse velocity fluctuations, \(v\), are presented in Fig. 5. Peaks are observed near 100 Hz, which is close to the natural frequency. The natural frequency of the mixing layer \(f_n\) is approximately 130 Hz based on stability analysis and measured data (not shown). The peak frequency decreases in downstream locations; at \(x = 50\) mm the frequency is near 200 Hz, and it decreases to approximately 80 Hz at \(x = 200\) mm. It was considered that the higher frequency perturbation observed at upstream locations was the result of wake of the splitter plate. The peak frequency gradually decreases, and the characteristics of the mixing layer become apparent(22). We imposed the perturbations with three different frequencies, 30 Hz, 60 Hz and 140 Hz, which correspond approximately to \(f_n/4\) (second sub-harmonic), \(f_n/2\) (first sub-harmonic), and \(f_n\) (natural frequency) in the present case.

3.3. Flow with forcing

We show the development of the flow with different perturbations. Table 2 summarizes measurement conditions: six combinations of frequency and amplitude in addition to no control cases. Hereafter, we refer to these different experiments by the cases indicated in Table 2. It was confirmed through the measurements at different spanwise locations \((-60\) mm \(\leq z \leq 60\) mm) that the spanwise non-uniformity of the forcing was negligibly small in the present measurement locations.

First, the locations of the center of the mixing layer \(y_{0.5}\) are shown in Fig. 6(a-c). It is indicated that in all cases, the flow spreads more into the lower velocity side. In the cases of \(f_c = 30\) Hz, the effect of amplitude is not so apparent except for case \(f30A2\). In case \(f140A0.5\), the spreading rate of the flow is reduced by forcing, which is the opposite effect compared with other frequencies \(f_c = 30\) Hz and 60 Hz.

Figure 7(a-c) shows the development of the vorticity thickness. The values are normalized by the vorticity thickness at the most upstream location of the no forcing case, \(\delta_{\omegaA25}\). At the location farthest downstream \(x = 200\) mm, case \(f30A2\) gives the largest overall thickness among the cases, although case \(f60A1\) gives larger value than that of case \(f30A2\) at \(x = 50\) mm. In case \(f60A1\), the thickness rapidly increases until \(x = 100\) mm, it decreases slightly at \(x = 150\) mm, then increases again at the \(x = 200\) mm. On the other hand, for case \(f60A0.5\), the thickness continuously grows and it achieves nearly the same thickness as case \(f60A1\) at \(x = 150\) mm and 200 mm. When we compare results of constant amplitude cases,
case $f60A0.5$ achieves greatest development, and the effect of forcing is not apparent in case $f30A0.5$. It should be noted that in case $f140A0.5$, the vorticity thickness at $x = 200$ mm is smaller than that of case $PF A3NC$. This indicates that the development of the vorticity thickness is suppressed by the forcing. In addition, the difference among the no control cases using different PFAs are found. This may be attributed to the slight disagreement of the inlet boundary conditions, e.g., turbulence created at the edge of the polycarbonate plate. The development of the momentum thickness (not shown) is found to be similar to that of the vorticity thickness.

Figure 8 presents the development of the streamwise mean velocity distribution. The transverse position is normalized by $\delta_2^{14}$. The velocity profiles of the different frequencies with the constant amplitude, $A = 0.5$ mm, are shown in Fig. 8(a), and the velocity profiles of the different amplitude with constant frequency, $f_c = 60$ Hz, are shown in Fig. 8(b). For different frequencies with constant amplitude, the obvious differences are found among profiles at downstream locations, whereas the differences are relatively small at upstream locations. In particular, case $f140A0.5$ shows a larger velocity gradient near the center of the mixing layer than that of a case without forcing. Such shape of the mean velocity profile results the smaller vorticity and momentum thicknesses. The effect of the amplitude is apparent in upstream locations, $x = 50$ mm, but at the downstream locations $x = 150$ mm and 200 mm, two velocity distributions with forcing cases look similar.

Before we look at the velocity fluctuations of different cases, we introduce the three component decomposition\(^{(23)}\) of the instantaneous velocity, which decomposes it into mean, periodic and turbulent components as follows:

$$u_i = U_i + \tilde{u}_i + u'_i,$$

where $U$ is the mean velocity, $\tilde{u}$ is the periodic component at the forcing frequency, and $u'$ is the turbulent component. The control input is used for the reference signal of phase averaging. One period of the reference signal is divided into 20 slots and the phase-averaged value is calculated from the measured samples inside each slot. The number of samples used for each phase-averaged value is approximately 15000. These velocity fluctuations are also normalized by the velocity difference, i.e., $\tilde{u}_i^* = \tilde{u}_i / U_i$, and $u'_i^* = u'_i / U_i$. The periodic components $\tilde{u}_i^*$

\[\text{Fig. 6 Location of the center of the mixing layer; (a) PFA-1, (b) PFA-2, (c) PFA-3.}\]

\[\text{Fig. 7 Development of the vorticity thickness; (a) PFA-1, (b) PFA-2, (c) PFA-3.}\]
and $\tilde{\psi}^2$, and the fluctuating components $\tilde{u}^2$ and $\tilde{v}^2$ of the constant amplitude ($A = 0.5$ mm) cases are plotted in Fig. 9. Substantial differences are observed among flows with three control inputs. The distributions show qualitative differences: the periodic components $\tilde{u}^2$ shows one main peak in the case $f=30A0.5$. However, the profiles of cases $f=60A0.5$ and $f=140A0.5$ show two peaks. In addition, the transverse periodic velocity component $\tilde{v}^2$ of cases $f=60A0.5$ and $f=140A0.5$ are substantially larger than that of case $f=30A0.5$ although the developments of cases $f=60A0.5$ and $f=140A0.5$ are different. As for the turbulent components, at the most downstream location the turbulent fluctuation is suppressed at the center in cases $f=30A0.5$ and $f=60A0.5$: the latter achieves greater suppression of the turbulent component. On the other hand, in case $f=140A0.5$, the fluctuating components become significantly larger than other cases.

We look on the power spectral density (PSD) at the center of the mixing layer in order
to determine the spectral contribution of the forcing. Figure 10 shows the PSD of transverse velocity $v$ at $y_{0.5}$ and $x=200$ mm. The PSD of case $f30A0.5$, $f60A0.5$, and $f140A0.5$ are shown in Fig. 10(a), and the PSD of case $f60A1$ and $f60A0.5$ are shown in Fig. 10(b). For the cases with constant amplitude, $A=0.5$ mm, perturbation of $f_c=60$ Hz is most effective for the suppression of velocity fluctuations at frequencies other than $f_c$ and its harmonics, and in case $f140A0.5$, velocity fluctuations increases in the wide frequency range. For the cases with constant frequency, $f_c=60$ Hz, velocity fluctuations at frequencies other than $f_c$ and its harmonic component are reduced.

In order to check the effect of the forcing on the total velocity fluctuation, we defined the integral periodic and turbulent velocity variances as:

$$
\tilde{\bar{U}}_i = \int_{-\infty}^{\infty} \tilde{u}^2_i dy^*, \quad U'_i = \int_{-\infty}^{\infty} u'^2_i dy^*,
$$

The estimated integral velocity variance are presented in Fig. 11. The integral values of fluctuating velocity variance are not suppressed due to the forcing, although a significant reduction
4. Discussion

We focus on a periodic flow structure excited by forcing. Figure 12 presents the velocity vectors of cases $f_{30}A_2$, $f_{60}A_1$ and $f_{140}A_{0.5}$ against $y$ and convection distance, $x_c = x/U_s/(2nf_c\phi)$. The free stream velocity differences $U_s$ in (a), (b) and (c) are identical.

of the turbulent component near the center of the mixing layer is observed as shown in Fig. 9. In case $f_{60}A_1$, the streamwise turbulent component decreases slightly whereas the transverse component does not change. In the cases of $f_c = 30$ Hz, the periodic component of the transverse velocity fluctuations monotonically increases in the downstream direction. On the other hand, in case $f_{60}A_1$ and $f_{140}A_{0.5}$, the periodic velocity fluctuations reach their peak value then decrease. In particular, in case $f_{140}A_{0.5}$, as the periodic component decreases, the fluctuating component increases.

Fig. 12 Pattern of the periodic velocity component at different streamwise locations; (a) case $f_{30}A_2$, (b) case $f_{60}A_1$ and (c) case $f_{140}A_{0.5}$. The free stream velocity differences $U_s$ in (a), (b) and (c) are identical.
Fig. 13 Profiles of the periodic and fluctuating components of the production terms.

Fig. 14 Profiles of the periodic and fluctuating components of the Reynolds shear stress.

The estimated production terms $\tilde{P}_{12}$ and $P'_{12}$ are shown in Fig. 13. In addition, the periodic and turbulent components of the Reynolds shear stress corresponding to the production
terms are shown in Fig. 14. In cases $f_{30A2}$ and $f_{60A1}$, $P'_{12}$ gets closer to zero and $\tilde{P}_{12}$ becomes much larger than $P'_{12}$ at downstream locations. For case $f_{140A0.5}$, although $P'_{12}$ does not change with streamwise position, $\tilde{P}_{12}$ gradually decreases in streamwise locations.

The previous studies\(^{(13,14)}\) reported that the Reynolds shear stress, $\overline{u'v'}$, might take the opposite sign from that expected from the direction of the mean shear due to the slight inclination of the vortex lumps. These observations are consistent with the present results of case $f_{140A0.5}$, where the periodic component is found to be positive as shown in Fig. 14, and the distinct stable vortical structure is observed as indicated in Fig. 12(c). In the present case, however, since the inflow conditions are a turbulent boundary layer, the production of the turbulent component of the Reynolds shear stress is fairly large and the overall Reynolds shear stress remains negative.

Note that the distributions of the periodic production terms of the shear stress $\tilde{P}_{12}$ take negative value in all cases studied in the present study even in the case where the periodic Reynolds shear stress $\overline{u'v'}$ becomes positive. In fact, the Reynolds shear stress is determined by the balance of all terms in the transport equation including those unavailable in the present measurement. For more a rigorous discussion, one should evaluate the balance of all terms in the transport equation.

5. Conclusion

We conducted the experiments in a turbulent mixing layer with periodic forcing. Three different lengths of a Piezo Film Actuator (PFA) have been used, and various combinations of forcing amplitude and frequency are introduced at the inlet of the mixing layer. Due to the forcing at first and second sub-harmonic frequencies against the natural frequency, the development of the vorticity and momentum thicknesses is enhanced. On the other hand, the forcing near the natural frequency suppresses the development of the mixing layer. This can be explained from the mean streamwise velocity distributions: in low frequency cases, the mixing layer spreads due to the forcing; however, the mean velocity gradient becomes steeper with the forcing near the natural frequency. From the evaluation of the integral of the velocity fluctuations, the total amount of turbulent velocity fluctuations across the mixing layer is nearly constant (although the peak values of the velocity fluctuations are greatly suppressed). The differences found in the fundamental statistics are explained from the pattern of the velocity vector. In the second sub-harmonic case, a forcing creates the periodic perturbation, but the vortex is found only in the downstream region. On the other hand, when forcing at higher frequencies, an apparent vortical structure is observed. In particular, when the forcing near the natural and its sub-harmonic frequencies, two stable counter rotating vortices are clearly observed in one period of forcing. Moreover, spatial development of the estimated production terms clearly shows the difference in cases with different frequencies. By forcing at lower frequency, the turbulent component of the production term decreases in the downstream region, although it is nearly constant in the case of forcing near the natural frequency. The overall Reynolds shear stress remains negative due to the contribution of the turbulent component even when the periodic component becomes positive.

References


