Impact of wing-tip vibration on the development of a wing-tip vortex

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Abstract
External forcing on a wing-tip vortex can affect its instability, and therefore an optimal perturbation can improve the aerodynamic performance of the wing. The present study examined the unsteadiness of the wing-tip vortex under periodic wing-tip vibration, and revealed its effect on the aerodynamic performance of the wing. A 3D-printed vibrating wing-tip model was prepared, which was driven by a sheet-type piezo actuator. Phase-averaged stereo particle image velocimetry (PIV) measurements clarified that the averaged position of the vortex depends on the phase of the wing-tip vibration, and the vortex shifted further from the wing as the actuation frequency increased. The phase-averaged velocity distributions indicate that the velocity deficit inside the vortex is significantly enhanced near the end of the downstroke of the wing-tip motion. The wing-tip vortex is weakened in the mid-upstroke, and its impact depends on the actuation frequency. This is because the motion of the wing is in the same direction as the flow rolling up from the pressure side, which prevents the formation of the vortex. In the mid-upstroke phase, the turbulence quantities, e.g., the turbulent kinetic energy and the Reynolds shear stress, are significantly suppressed; these effects depend monotonically on the actuation frequency. These arguments are supported by time-resolved recordings of the flow and the wing motion. The force measurements reveal that the vibration of the wing-tip brings a positive effect on the lift-to-drag ratio.

Keywords: Wing-tip vortex, Active flow control, Particle image velocimetry, Turbulence statistics, Aerodynamic performance

1. Introduction

A wing-tip vortex is formed as an inevitable by-product of lift generation. It often causes negative effects in engineering applications, e.g., induced drag of aircraft (Marec, 2001; Abbas et al., 2013), limiting flight frequency at airports (Robinson, 1996), noise from turbo machinery including wind turbines (Brooks and Marcolini, 1986; Yung, 2000), and cavitation by hydrofoils (Arndt, 2002). In aerodynamic applications, the impact of the wing-tip vortex is mitigated by passive wing-tip devices such as winglets (Whitcomb, 1976) that modify flows near the wing-tip. Lee (2011) tested the effect of perforated Gurney flaps on the growth and development of a tip vortex, and found that the lift-to-drag ratio was influenced by the size of holes on the flap surface. The effects of these passive devices have been summarized in Kroo (2001). Due to the rapid emergence of unmanned air vehicles, the aerodynamic characteristics of wing-tip vortices of small scale aircraft have extensively been investigated. Lynch et al. (2018) tested the aerodynamic performance of a bioinspired wing-tip, which is a wing-tip with gaps mimicking a wing of a bald eagle. They reported improvements in lift and drag characteristics versus the conventional wing-tip. Although these passive devices can readily be designed and installed, each device is optimized to address a specific condition or set of conditions, and therefore it is difficult to design passive devices that provide optimal performance over the whole range of flight conditions.

Because of this limitation, active flow control devices have been actively sought to achieve higher aerodynamic performance and flexible operation able to adapt to varying flight conditions. Crouch et al. (2001) introduced perturbations in a wing wake using vibrating flaps and ailerons to stimulate unstable modes, and succeeded in accelerating the decaying
process of the wake. Heyes and Smith (2004) employed steady and pulsed blowing to introduce fluctuations for a similar purpose, and identified control effects on the structures and the positions of the wing-tip vortex. Dghim et al. (2018) applied synthetic jets with different strengths and frequencies, and investigated their impacts on the vortex structures. Under optimal conditions, turbulent fluctuations emerge in the core of the vortex, and they promote diffusion of the wing-tip vortex. Guha and Kumar (2017) used a vibrating winglet to affect the initial development stage of the wing-tip vortex. Their work indicated that the winglet vibration induces a periodic meandering, and the distributions of the time-averaged statistics are elongated and diffused. Though it has been demonstrated that the oscillation of the wing-tip can influence the development and decaying process of the vortex, unsteady phase dependent structures of the vortex have not yet been clarified.

Because of its importance in engineering applications, fundamental characteristics of the wing-tip vortex have been rigorously investigated. The wing-tip vortex flow has also been considered as a canonical flow test case with a strong longitudinal vortex. Reviews are available in Spalart (1998); Kroo (2001); Leweke et al. (2016). The fundamental turbulence characteristics, e.g., the mean velocity and the Reynolds stresses, have been characterized by experiments and numerical simulations. Devenport et al. (1996) performed hot-wire measurements, and revealed the characteristics of the developing wing-tip vortex in the mid- to far-field. Chow et al. (1997) performed experiments in the very near region including on the suction side of the wing. It is known that the wing-tip vortex realized in a wind-tunnel often causes meandering, and it makes a significant impact on the statistical characteristics. Inside a wing-tip vortex, steep gradients of the velocity and pressure take place, and strong velocity and pressure fluctuations are caused by the meandering motion. Naka et al. (2009) performed simultaneous measurements of velocity and fluctuating pressure using a combined probe consisting of an X-type hot-wire and a fluctuating pressure probe. The characteristic patterns in the Reynolds stress and the pressure fluctuations can be associated with the meandering motion of the wing-tip vortex. It is known that the amplitude and the frequency of meandering are determined by the surrounding environment. Bailey et al. (2018) investigated the effect of the free stream turbulence on the meandering motion of a wing-tip vortex. They stated that the amplitude of the meandering motion can be scaled with the ambient turbulence intensity, and that the period is scaled by the vortex turn over time. These findings imply that the development and decay processes of a wing-tip vortex strongly depends on the boundary conditions.

The present study aims to understand the effects of forcing on the development of the wing-tip vortex. The forcing is introduced by the vibration of the wing-tip. The development of the wing-tip vortex is evaluated using phase-locked stereo particle image velocimetry (PIV) measurements. In addition, the effect of the wing-tip vibration on the aerodynamic performance of the wing, i.e., the lift and drag forces, is evaluated.
2. Experiment

2.1. Vibrating wing-tip device

The wing model with the vibrating tip-device is shown in Fig. 1(a). The present wing model consists of two parts: the base wing and the vibrating wing-tip device. The base wing is made of aluminum alloy having a section of NACA0012 with the chord length $c = 100$ mm and the wing span $b = 150$ mm. The wing-tip part is a curved rectangular resin plate. The thickness of the plate is 1.5 mm. Schematic diagrams of the wing-tip device are given in Fig. 1(b)-(d). The angle of attack is denoted as $\alpha$. The positive angle of attack of the wing means that the concave surface becomes the suction side of the wing as presented in Fig. 1(b). The wing-tip plate was fabricated using a 3D printer (Objet350 Connex3, Stratasys) with acrylic ultraviolet curing resin (Vero White Plus, Stratasys). The joint part is beveled so that the wing-tip device is smoothly connected to the base wing. The vibration of the wing-tip device is generated using a sheet-type piezo actuator (Macro Fiber Composite MFC8557, Smart Material) with the size of $103 \times 64 \times 0.3$ mm. The dimensions of the curved resin plate were determined to fit the size of the piezo actuator. The piezo actuator is fixed on the convex surface using an epoxy-type adhesive (DP460, 3M) by the vacuum bagging technique. Hereafter, this wing-tip device is simply called the wing-tip. The curved surface is employed so that the significant displacement in the direction perpendicular to the surface of the actuator can be obtained from the in-plane deformation of the piezo actuator. The vibration mode of the present wing-tip device is the first bending mode, and no other mode is apparently observed. The driving voltage is provided to the piezo actuator through the thin copper tape attached on the base wing as shown in Fig. 1(a). The sinusoidal voltage signal is generated from a function generator (WF1994, NF Corp) or a multi-function I/O device (PCIe-6361 and BNC-2110, National Instruments). The latter was employed when the wing-tip motion needed to be synchronized with the data acquisition. The signal from the function generator was boosted by 200x using an amplifier (PA05039, TREK). For the vibration with the maximum amplitude condition, the operating voltage of the actuator is a sinusoidal signal between $-500$ V and 1500 V.

The vibration characteristics were measured using a laser distance sensor (HG-C1100-P, Panasonic). When the maximum input voltage was applied to the actuator at frequencies up to 20 Hz, the amplitude was measured to be 6 – 8 mm. Here, the amplitude in the direction perpendicular to the surface was measured at the tip of the device and the center in the chord-wise location. The vibration amplitude increased near the resonance frequency, which was found to be slightly higher than 30 Hz; the amplitude was 16.2 mm at 30 Hz.

2.2. Wind-tunnel and experimental conditions

An open blowing type wind-tunnel was used for the present experiments. The flow from a blower is directed by a honeycomb and three stainless steel screens and accelerated by a converging nozzle with an exit section area of $40 \times 40$ cm. The contraction ratio is 9:1. The maximum flow velocity at the exit is 13 m/s, and the turbulence intensity at the center part is 0.8 % at the exit velocity of 7 m/s. The velocity was monitored by a Pitot tube (LK-15, Okano works) with a differential pressure transducer (DP45, Valyline and PA701, Krone).

The wing model was placed at the exit of the wind tunnel. Three coordinate systems are used in the present study as shown in Fig. 1(b). The first coordinate system $x-y-z$ is referenced at the leading edge of the wing, the second coordinate system $x_t-y_t-z_t$ is defined at the trailing edge of the wing-tip device, and the third coordinate system $x_c-y_c-z_c$ is based on the center of the wing-tip vortex. The streamwise direction is $z$, the direction of the wing span is $y$ and $x$ is defined perpendicular to $y$ and $z$ axes. At $\alpha = 0^\circ$, the leading edge of the base wing was located at 20 mm downstream from the exit plane of the wind-tunnel and at the center in $x$ direction, and the root of the base wing was positioned at the same surface of the wind-tunnel bottom wall. The free stream velocity, $U_\infty$, was set to 7 m/s giving the chord Reynolds number, $Re_c = 4.6 \times 10^4$.

The experimental conditions are summarized in Table 1. The key experimental parameters are the angle of attack $\alpha$ and the actuation frequency $f$. The normalized actuation frequency is defined as $f^* = fc/U_\infty$. Three values for the

| angle of attack, $\alpha$ [deg] | normalized amplitude, $A^* = A/c$ | normalized frequency, $f^* = fc/U_\infty$ |
|-------------------------------|-----------------------------------|-----------------------------------------|
| 3.0                           | 0.050                             | 0.043, 0.071, 0.10                      |
| 7.0                           | 0.070                             | 0.20, 0.27, 0.34                       |
| 10                            | 0.085                             | 0.26, 0.37, 0.43                       |
angle of attack were investigated: 3.0°, 7.0° and 10°. For each angle of attack, the amplitude of the wing-tip vibration, $A$, was kept constant, and a range of actuation frequencies were investigated. The largest amplitude achievable for the frequency range of each angle of attack was taken. These were determined from our preliminary experiments. For the higher angle of attack, a stronger wing-tip vortex is created and a higher actuation frequency is necessary to effect the vortex. This suggests that the effect of the wing-tip vibration on the wing-tip vortex is scaled by the ratio of the maximum circumferential velocity of the wing-tip vortex to the maximum velocity of the wing motion.

2.3. Stereo PIV

Figure 2 presents the schematic of the stereo PIV setup. The measurements were conducted at different streamwise positions at $z/c = 1.5, 2.5$ and $4.0$. A laser beam of the 532 nm-wavelength from a pulsed laser with the maximum output energy of 140 mJ/pulse (Evergreen, Quantel) was guided and shaped to a planar sheet perpendicular to the free stream. The center of the light sheet was aligned to the center of the wing-tip vortex identified in the preliminary experiment. The thickness of the light sheet was adjusted to approximately 5 mm using a plano convex–concave lens system. The tracer particles (bis(2-ethylhexyl) sebacate) had a diameter range of 0.3–1.0 $\mu$m; they were produced by a particle generator (PIVpart14, PIVTEC) and introduced upstream of the blower. The Stokes number based on the characteristic time of the particle and that of the flow at the representative condition, where $\alpha = 7^\circ$ without wing-tip vibration, is evaluated to be $1.07 \times 10^{-3}$. Here, the characteristic time of the flow is estimated using the diameter of the vortex core and the maximum circumferential velocity.

Two CMOS cameras (CLF-C2880M, Imperx, 2832 × 2128 px) with 50 mm F#1.4 lenses (Samyang 50mm F1.4 AS UMC) were oriented at 45° relative to the measurement plane, as shown in Fig. 2. The lens and the camera were connected through an in-house made Scheimpflug adapter, and a clear uniform focus on the particles was achieved. The arrangement of the laser and the cameras took advantage of the forward scattering of the laser light from the particles. The cameras and the laser were synchronized by a delay pulse generator (Quantum composer 9618). The image acquisition was performed at 2 Hz.

A calibration grid was recorded for the conversion of the image onto physical coordinates. The grid was traversed in the direction perpendicular to the grid plane with a step of 1.0 mm. The grid position closest to the laser light sheet was identified by the self-calibration procedure (Wieneke, 2005), and misalignment of the calibration grid plane and the laser light sheet plane was corrected. A third-order polynomial function was used for mapping between the image coordinate and the physical coordinate (Soloff et al., 1997). A linear mapping matrix was obtained from the two pairs of the in-plane image coordinates on the two cameras and the physical coordinate. The laser light sheet thickness, which can be obtained from the self-calibration, was approximately 5.3 mm in the center of the measurement region. This relatively thick light sheet is necessary to let particles stay inside the light sheet in the duration of two pulses of PIV as it is known as a quarter rule (Adrian and Westerweel, 2010). The separation of two frames was set to 150 $\mu$s. This interval should be long enough to capture the in-plane motion of particle, but still less than the particles residence time in the light sheet. The resolution of each raw particle image was 35.6 $\mu$m/px and 26.4 $\mu$m/px in $x$ and $y$ directions, respectively.

Particle images were processed using an in-house PIV code based on previously published techniques (Adrian and Westerweel, 2010; Raffel et al., 2018). The code employs an FFT-based multi-pass cross correlation method with three point Gaussian subpixel interpolation and outlier detection based on Westerweel and Scarano (2005). Details of the PIV analysis are found in our previous paper (Naka et al., 2020). For the present analyses, the interrogation window with the
size of 128×128 px, was used for the first pass, and 64×64 px for the final pass. The latter window size provides the spatial resolution of approximately 3.2 mm. The spacing between adjacent vectors was set to 32 px, which gives 50 % window overlap. The three components of the displacement were obtained by the mapping conversion matrix using the two pairs of in-plane displacements from the two cameras. The statistics were evaluated by averaging 500 velocity snapshots.

The results of the present stereo PIV experiments were validated through a preliminary experiment in the wake of a circular cylinder. The stereo PIV measurements in the wake of a circular cylinder at ten-diameter-length downstream from the center of the cylinder were performed with the same configuration as that for the wing-tip vortex. The results of the present measurements were compared to those in the literature (Ong and Wallace, 1996). Using 100 samples, the time-averaged velocity and the second moment of the velocity fluctuations exhibit discrepancies of 3.0% and 21%, respectively. Since the measurements in the wing-tip vortex employ 500 samples for statistics, the measurement uncertainty can be estimated as approximately 2% and 10% for the time-averaged velocity and the second moment of the velocity fluctuations, respectively.

2.4. Phase-locked measurement

A series of phase-locked measurements were performed to characterize the periodic nature of the flow. The image acquisition of the stereo PIV was synchronized with the driving signal of the wing. Figure 3 shows the relationship between the phase of the applied voltage and the motion of the wing-tip. The phase-locked measurements were performed at three representative phases, i.e., \( \phi = 0^\circ, 90^\circ \) and \( 270^\circ \). These phases correspond to the middle of the upstroke, the end of the upstroke, and the end of the downstroke, respectively. Here, the input signal and the wing motion are expected to be in-phase because the results in different actuation frequencies are consistent. The objective of the present measurements is to compare effects of actuation at different phases. To compensate for different measurement locations in the streamwise direction, the time delay due to convection is defined as \( \Delta T = \Delta z/U_\infty \), where \( \Delta z \) is the distance in the streamwise direction from the trailing edge to the measurement plane. The timing of the laser flash is delayed for \( \Delta T \), for example, \( \Delta T = 42.9 \) ms for the measurement at \( z/c = 4 \). The statistical characteristics at the different phases are quantified by averaging samples at a specific phase. Hereafter, this averaging procedure is called phase-averaging.

2.5. Force measurement

The drag and lift acting on the wing were measured using a two-component force sensor (LMC-3501-5N, Nissho Electric Works). The axes of the force sensor were aligned so that the drag and the lift of the wing could be directly measured. The data were acquired by a strain measurement unit (NR-ST04, Keyence). The driving voltage signal was simultaneously measured using an analog signal measurement unit (NR-HA08, Keyence). The strain measurement unit and the analog signal measurement unit were synchronized and controlled by a data logger (NR-500, Keyence).

Operating conditions were the same as those for the PIV measurements. For each condition, the sampling frequency was set to 10 kHz and the sampling time was 20 s. These data were averaged to obtain time-averaged values of the lift and the drag.

The results of the present measurement were validated against the data in the literature (McAlister et al., 1978). The increment ratios of the lift and drag between the angles of attack 7° and 10° are close to each other: the increment ratios of lift and drag in McAlister et al. (1978) are approximately 43% and 45%, respectively; those in the present study are approximately 41% and 38%, respectively.
Fig. 4 Schematic of the vortex center identification. The center of the vortex is identified when the surrounding neighbor points consistently indicate a swirling motion. $i$ and $j$ indicate the indices of the velocity vector field in $x$ and $y$ directions, respectively.

Fig. 5 Distributions of the center of vortex for different actuation conditions at $z/c = 4.0$.

2.6 High-speed 2C2D PIV
The unsteady characteristics of the vortex formation were identified by flow visualization using a high-speed camera with a 105 mm lens and a continuous wave laser. The laser sheet was placed just downstream of the wing, $z/c = 1.05$. The planar two-component two-dimensional (2C2D) PIV was performed, and the velocity distributions in the plane perpendicular to the free stream were obtained.

3. Effect of the wing-tip vibration on the flow characteristics
In the parameter space investigated, a particular focus is given to the case in which the angle of attack is $7^\circ$, since it was most representative in terms of the effect of the wing-tip vibration on the flow characteristics. Results of the other conditions are mentioned when necessary.

3.1 Vortex meandering
The wing-tip vortex exhibits a meandering motion even when no actuation is applied. To investigate the effect of the actuation on the vortex itself, the averaging was performed at the coordinate fixed at the center of the vortex. For each velocity snapshot, the center of the wing-tip vortex was identified. To extract the center of a vortex from the velocity field, a number of methods are available in the literature (Tanahashi et al., 1999; Chakraborty et al., 2005). In this study, the vortex center was identified by a swirling motion judged by the eight surrounding points as indicated in Fig. 4. The identification was performed on a grid ten times finer than the original PIV grid. The velocity field for the identification was obtained by a cubic interpolation. The uncertainty of the position of this identification is $\pm 80\, \mu m$, corresponding to the width of the grid used for the identification. The density of the finer grid is chosen rather intuitively with the idea that the finer grid with its width one order of magnitude less than the original grid is enough to determine the center of the vortex accurately. If multiple vortex centers were detected in the fields, the one with the largest vorticity magnitude was taken as the center of the wing-tip vortex.
Fig. 6 Development of the time-averaged velocity distributions for no-control cases.

Fig. 7 Distributions of the phase-averaged velocity for different actuation frequencies at $z/c = 4.0$, $\phi = 0^\circ$ (top), $\phi = 90^\circ$ (middle), $\phi = 270^\circ$ (bottom).
at this plane distribute within a circle with a diameter of approximately 0.08c. Here, the no-control case denotes the case without wing-tip vibration. The results indicate that the wing-tip vibration does not significantly change the amplitude of the meandering motion. However, the center of the distribution clearly depends on the phase of the wing-tip vibration, and slightly depends on the frequency. For the highest actuation frequency \( f^\ast = 0.34 \), the center of the distribution moves away from the wing-tip compared to the lower frequency cases.

### 3.2. Time-averaged and phase-averaged velocity characteristics

Figure 6 shows the distributions of the time-averaged velocity for the no-control cases at different streamwise locations. The field of view corresponds to a square region with 0.32c \( \times \) 0.32c. As explained in Sec. 3.1, these time-averaged velocity fields were obtained based on a coordinate system with its origin at the center of the vortex. At the farthest downstream location, the velocity deficit (where \( U_z/U_\infty \leq 1.0 \)) is mostly observed inside the vortex. This deficit reaches at most 18% of the free stream velocity. In the upstream region, \( z/c = 1.5 \), another decelerated region is observed on the left part of the vortex. This may be associated with a shear layer rolling up from the wing, and is still observable at \( z/c = 2.5 \). Therefore, in the upstream regions, the formation of the vortex is underway, and is mostly completed at \( z/c = 4 \).

Figure 7 shows the phase-averaged velocity distributions at \( z/c = 4 \) for different frequencies (\( f^\ast = 0.20, 0.27, \) and 0.34) and different phases (\( \phi = 0^\circ, 90^\circ, \) and 270°). Compared to the no-control case shown in Fig. 6, the velocity deficit is significantly reduced for all the actuation frequencies at \( \phi = 0^\circ \). At \( \phi = 90^\circ \), the velocity deficit gradually drops as the actuation frequency increases. The velocity deficit is suppressed for \( f^\ast = 0.27 \), and 0.34. At \( \phi = 270^\circ \), the velocity deficit becomes more significant than that in the no-control case, and its effect increases with the actuation frequency. For \( f^\ast = 0.34 \), the maximum velocity deficit is found at the center of the vortex, where the velocity is 37.6% below the free stream velocity. From these observations, the velocity deficit is reduced in the upstroke phase of the wing-tip vibration, and increases in the downstroke phase. In the downstroke phase, the apparent angle of attack increases due to the motion of the wing-tip, and it enhances the low streamwise momentum region near the wing surface. Then, that low momentum fluid is rolled up and forms a significant velocity deficit. For the upstroke phase, the apparent angle of attack decreases, and the formation of the low momentum fluid is less significant.

Figure 8 shows the profiles of the circumferential velocity, \( v_\theta \) along the radial direction, \( r \). The profiles are obtained by averaging the circumferential velocities over the circumferential direction. Although the velocity distribution was not perfectly axi-symmetric, the circumferential averaging was performed so that the representative velocity profile could be obtained. For the no-control case, the shape of the profile has a sharp peak close to the center \( r/c = 0.02 \) indicating that the vortex core is concentrated in this region. The dependence of the phase in the circumferential velocity profile is similar for all the frequencies. The peak present under the no-control case at the phase angle \( \phi = 0^\circ \), disappears, and the diameter of the vortex increases with the actuation frequency. Here, the radius of the vortex core is defined at the location of the maximum circumferential velocity in the profiles of \( v_\theta \). On the other hand, at the phase angle \( \phi = 90^\circ \), the shape of the profile is similar to the no-control case, and at \( \phi = 270^\circ \), it is in between those for \( \phi = 0^\circ \) and 90°. In terms of the circumferential velocity profile, the radius of the vortex is largest at \( \phi = 0^\circ \). However, as shown in Fig. 7 the most significant velocity deficit is observed at \( \phi = 270^\circ \). The phase of the largest radius, \( \phi = 0^\circ \), does not coincide with that of the most significant velocity deficit, \( \phi = 270^\circ \). This indicates that the swirling motion and the velocity deficit are not directly linked.
3.3. Vorticity and turbulence characteristics

Figure 9 shows the distributions of the axial vorticity $\zeta$ at $z/c = 4$ and $\phi = 0^\circ$. The vorticity was computed using a second order central differencing scheme on the PIV grid points. For the no-control case, the vorticity distribution has a peak at the center of the vortex. The blue-dashed contour line indicates vorticity values 12% of the maximum, and equates to a diameter of approximately 0.15$c$. With actuation, the peak values of the vorticity decreases as the actuation frequency increases at $\phi = 0^\circ$. At $f^* = 0.34$, the reduction rate $\eta$ is approximately 71%. Here, the reduction rate is defined as $\eta = 1 - \zeta_{\text{max,control}}/\zeta_{\text{max,no control}}$. In addition, the contour line encompasses a larger area compared to the no-control case. This indicates that the vortex becomes weak and larger in radius due to the wing-tip vibration at $\phi = 0^\circ$. These weakened vorticity distributions can be explained from the radial profiles of the circumferential velocity shown in Fig. 8. For the other phases $\phi = 90^\circ$ and $270^\circ$ (not shown), no significant reduction of the vorticity is found.

Figure 10 shows the distributions of the turbulent kinetic energy at $\phi = 0^\circ$. For the no-control case, the turbulent kinetic energy exhibits significant value slightly off the vortex center. The intensity of the turbulent kinetic energy becomes weaker for higher control frequencies. It stays visible at $f^* = 0.20$ and 0.27, and disappears at $f^* = 0.34$. Comparing the no-control and $f^* = 0.34$ cases, the maximum values of the turbulent kinetic energy dropped by 89%. It is noted that the reduction is found to be isotropic, which means that the components of the turbulent kinetic energy decrease mostly in the same ratio among three velocity components.

Figure 11 presents the distributions of the in-plane component of the Reynolds shear stress, $\overline{u'_w u'_y}$, at $\phi = 0^\circ$. The Reynolds shear stress is negative to the left of the vortex center and positive to the right. Similar to the distributions of the turbulent kinetic energy, the Reynolds shear stress reduces due to the wing-tip vibration, and the Reynolds shear stress dropped by 85% for $f^* = 0.34$ compared to the no-control case. It is noted that these components are obtained by phase averaging and using the reference frame with respect to the center of the vortex. The turbulent kinetic energy shown in Fig. 10 and the Reynolds shear stress shown in Fig. 11 correspond to the non-periodic turbulent components in the triple decomposition (Hussain and Reynolds, 1970). These results suggest that variations inside the vortex are suppressed when the external periodic actuation is imposed. The distributions of the turbulent kinetic energy and the Reynolds shear stress...
for the other phases, i.e., $\phi = 90^\circ$ and $270^\circ$ (not shown), are not significantly changed by the actuation frequency. These may indicate that the effect of actuation is less prominent at the phases, where the velocity of the wing-tip motion is zero.

These characteristics indicate that the turbulent components of the wing-tip vortex are significantly weakened at $\phi = 0^\circ$ corresponding to the mid-upstroke, where the vortex core is larger in size and smaller peak velocity in the circumferential velocity profile shown in Fig. 8.

3.4. **Characteristics in upstream locations**

Figure 12 shows the phase-averaged velocity fields with the wing-tip vibration at the upstream locations. In addition, the vorticity distributions at the corresponding streamwise locations and phases are shown in Fig. 13. For the phases associated with the upstroke, $\phi = 0^\circ$ and $90^\circ$, the wing-tip vortex is weaker or incompletely formed compared to the no-control case shown in Fig. 6. The magnitude of the velocity deficit is less than the one for the no-control case. Also, as shown in Fig. 13, the vorticity exhibits distributions larger in size compared to that of the no-control case, and the
magnitude is weaker than the one for the no-control case. On the other hand, at the end of the downstroke, $\phi = 270^\circ$, the velocity deficit is more evident than the one for the no-control case, which is the same tendency observed at the downstream location. The vorticity is concentrated at the center of the vortex during this phase. The comparison shown in Figs. 12 and 13 suggests that the vortex created during the upstroke phase are relatively weak compared to the one created during the downstroke phase.

Figure 14 presents instantaneous distributions of velocity vectors on the image frames from the high-speed recording at $\zeta/c = 1.05$. The angle of attack $\alpha = 7^\circ$ and the actuation frequency $f^* = 0.34$.

(a) $\phi = 0^\circ$  
(b) $\phi = 90^\circ$  
(c) $\phi = 270^\circ$

Fig. 14 Instantaneous distributions of velocity vectors superposed on the image frames from the time-resolved recording at $\zeta/c = 1.05$. The angle of attack $\alpha = 7^\circ$ and the actuation frequency $f^* = 0.34$.
The results at $\alpha = 10^\circ$ cannot be served to meaningful analyses since the force measured at this angle of attack is too small. For the angle of attack of $7^\circ$, lift coefficient stays mostly constant, but drag coefficients increase from $f^* = 0.20$ to 0.34, then decrease for $f^* = 0.43$, where it is the outside of the parameter scope of the stereo PIV experiment. The lift-to-drag ratio normalized by the value of the no-control case is slightly higher than unity because the decrease in drag is relatively larger than the one in lift. For the angle of attack of $10^\circ$, the lift coefficient stays near unity and the drag coefficient decreases very slightly for $f^* = 0.37$ and 0.43. The drag and the lift coefficients present non-monotonic behaviors suggesting several different mechanisms may be involved. These results should be interpreted with care, because the vibration of the wing-tip itself causes a large variation in the measured force signal. The measured force signal contains the aerodynamic contribution and the vibrational contribution. Therefore, the aerodynamic force was evaluated by subtracting the vibrational force which was obtained under the quiescent air condition from the measured force signal with the flow. The amplitude of the vibrational lift is found to be approximately 10 times larger than the aerodynamic lift of the wing, and the vibrational drag is approximately twice the value of the aerodynamic drag (not shown). Nevertheless, our observations suggest that the present actuation does not make a significant negative impact on the aerodynamic performance of the wing.

5. Conclusion

The effect of wing-tip vibration on the development of wing-tip vortices has been experimentally investigated. A vibrating wing-tip device was fabricated using a 3D-printed curved plate and a sheet-type piezo actuator. Phase-locked stereo PIV measurements were performed to characterize the unsteady nature of the wing-tip vortex.

The wing-tip vibration introduces a periodic perturbation, affecting the phase-averaged position of the vortex, whereas the amplitude of the meandering motion is less sensitive to the perturbation. The averaging procedure, based on a coordinate system with its origin at the center of the vortex, reveals key characteristics of the vortex itself. In the upstroke phase of the wing-tip vibration, the vortex is weakened because the wing-tip moves in the same direction as the fluid rolling up from the pressure side. On the other hand, during the downstroke phase, the wing-tip vortex is clearly established and the significant velocity deficits are observed. The excess of the velocity deficit during this phase is observed under different sets of conditions, e.g., different actuation frequencies and streamwise positions. The effects of the wing-tip vibration on
the turbulence quantities are evident in the middle of the upstroke motion. The turbulent kinetic energy and the Reynolds shear stress monotonically decrease with the actuation frequency. The time-resolved measurements taken just downstream of the wing support these arguments.

The force measurement quantifies the effect of the wing-tip vibration on the aerodynamic performance. The vibration induces a positive contribution in terms of the lift-to-drag ratio. However, the ratio’s dependency on the frequency exhibits non-monotonic behavior, suggesting that several different factors are relevant to this observed behavior.

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