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Sachin Y. Shinde and Jaywant H. Arakeri

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Jet meandering by a foil pitching in quiescent fluid

Sachin Y. Shinde[a] and Jaywant H. Arakeri[b]
Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560012, India

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The flow produced by a rigid symmetric NACA0015 airfoil purely pitching at a fixed location in quiescent fluid (the limiting case of infinite Strouhal number) is studied using visualizations and particle image velocimetry. A weak jet is generated whose inclination changes continually with time. This meandering is observed to be random and independent of the initial conditions, over a wide range of pitching parameters. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4800321]

Most of the natural swimmers and flyers use airfoil shaped appendages in flapping mode to generate thrust for propulsion. Inspired by this observation, oscillating foils are being looked at as potential replacements for conventional propellers in autonomous underwater vehicles (AUVs), micro air vehicles (MAVs), etc. In this connection, and also to understand the force generation mechanism in swimming and flying animals, several studies on oscillating foils have been conducted in recent decades (see the comprehensive reviews, Refs. 1–3, and the references therein). However, earlier research dates back to when Knoller in 1909 and Betz in 1912 independently reported that an airfoil heaving in moving fluid generates thrust.

An oscillating airfoil exhibits different flow regimes with change in Strouhal number, $St = fA/U_\infty$, where f is frequency of oscillation, A is peak-to-peak amplitude of airfoil trailing edge, and U_∞ is free-stream velocity. With increase in Strouhal number, the wake shows transition from 'drag-producing' to 'momentumless' to 'propulsive' (see Refs. 4–6). The vortical signature of a propulsive wake in two-dimensions is a symmetric reverse Bénard–Kármán vortex street.[4–7] However, beyond $St \approx 0.4$, the foil produces asymmetric wake, i.e., a vortex street inclined to the free-stream.[5] The Strouhal number, rearranged as $St = (A/U_\infty)/(1/f)$, can be interpreted as the ratio of the time scale of vortex convection to vortex formation. At high Strouhal numbers, perhaps the time for vortex convection is not sufficient so as to form the staggered pattern, but instead vortex pairs (dipoles) are formed. Godoy-Diana *et al.*[8] showed the dipoles are responsible for the generation of an inclined wake. Godoy-Diana *et al.*[5] conjectured that asymmetric wakes might be exploited by flying and swimming animals during maneuvering activities. It would be interesting to investigate the limiting case, which we consider in the present experiments, of infinite Strouhal number, i.e., zero free-stream condition ($U_\infty = 0$), i.e., a case relevant to hovering.

Only a few studies deal with an airfoil oscillating in still environment, though there are several with non-zero free-stream velocity (see, for example, Refs. 4–13 and the references in reviews[1–3]). Perhaps, Freymuth[14] was the first to observe a jet tilted with the horizontal stroke plane, produced in still air by a harmonically plunging and pitching rigid foil in what he called as 'mode 3' hovering motion; simulations by Gustafson *et al.*[15] showed the vortex patterns similar to 'mode 3' hovering. Experiments by Lai and Platzer[16] showed a deflected jet-like vortex street pattern for a NACA0012 foil heaving in still water. These studies (Refs. 14–16) reported a jet inclined in one orientation, but did not inform whether the jet changes orientation with time, i.e., "switching of the jet." The only known study that systematically investigates jet switching for rigid and flexible foils heaving in still water is the recent experimental work by Heathcote and Gursul.[17] They showed that jet switching is

[a]Electronic mail: sachin@mecheng.iisc.ernet.in
[b]Electronic mail: jaywant@mecheng.iisc.ernet.in

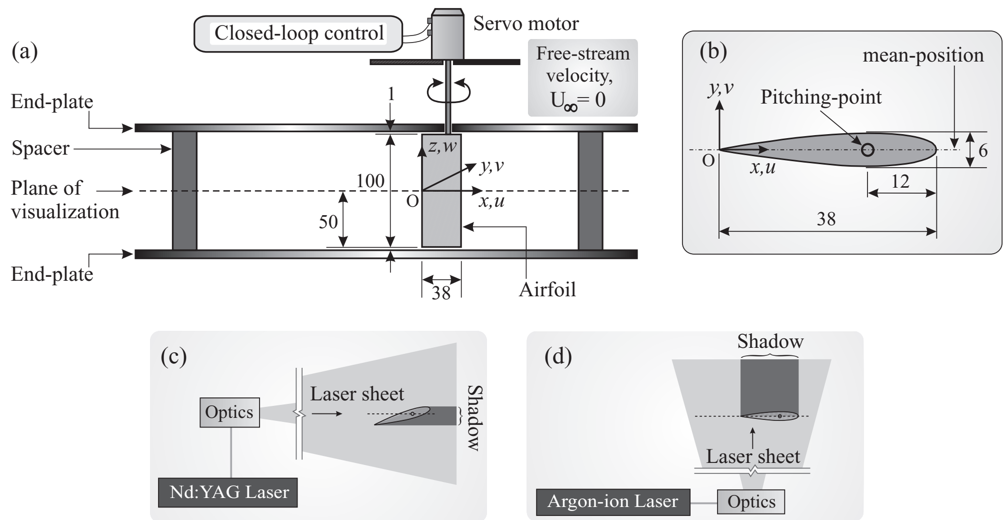

FIG. 1. Schematic of the (a) experimental setup, (b) sectional view of the airfoil. All dimensions are in mm. Note the coordinate system; x, y, z are, respectively, the streamwise, transverse, spanwise directions, and u, v, w are the corresponding velocities. The mean-position, about which the airfoil oscillates symmetrically, is the zero-angle position of airfoil chord. Schematics of the optics arrangement for (c) PIV measurements, (d) visualizations. Note the narrow shadowed region during PIV measurements. Note, (a) shows side view, and (b)–(d) bottom view.

quasi-periodic; switching frequency varies with heaving frequency and amplitude, and reduces with foil stiffness. This study is related to ours, and we will discuss it later.

However, the flow from an airfoil purely pitching in quiescent ambient has not been reported to the best of our knowledge. In this letter we investigate the flow produced by an airfoil with a sharp, rigid trailing edge pitching at a fixed location in quiescent water; also, we briefly discuss the effect of chordwise flexibility of foil on the flow.

The experiments are conducted in quiescent water in a glass tank ($800 \times 800 \times 350$ mm^3). Airfoil is confined between two end-plates with 1 mm gap on either sides [Fig. 1(a)]; spacers, kept away from the foil, do not affect the flow. The airfoil, made from a hard plastic (Acrylonytril Butadyne Sulphide), has NACA0015 symmetric profile with 38 mm chord (c) and 100 mm span [Fig. 1(b)]. A servo motor oscillates the airfoil sinusoidally about a pitching-point as, $\theta = \theta_{max} \sin(2\pi ft)$, where, θ is instantaneous pitching angle, t is time, θ_{max} and f are, respectively, amplitude and frequency of pitching.

The methods of investigation are flow visualizations and Particle Image Velocimetry (PIV). The flow is studied in a horizontal plane along the foil mid-span [see Fig. 1(a)], illuminated by a ~ 1 mm thick laser sheet. We used two optical arrangements: one, for the PIV measurements where the light sheet is passed from the downstream end to minimize the shadowed region [Fig. 1(c)], and the second, for the visualization experiments [Fig. 1(d)]. The visualizations were with fluorescein disodium salt (dye) and polystyrene particles (75–100 μm). For PIV, we used 30 μm hollow glass spheres as tracers, and proVISION–XS$^{\mathrm{TM}}$ Software (Release 3.03) from Integrated Design Tool, Inc. (IDT); 32×32 pixels interrogation windows with 50% overlap, spatial resolution is $0.064\,c$. The overall error is estimated to be about 1% of the instantaneous maximum streamwise velocity. See the supplementary material[18] for the PIV and the other experimental details.

The flow is studied for 12 cases: three amplitudes ($\pm10^\circ$, $\pm15^\circ$, $\pm20^\circ$) and four frequencies (1, 2, 3, 4 Hz). Since there is no free-stream flow in our experiments ($U_\infty = 0$), the reduced frequency ($2\pi fc/U_\infty$), and Strouhal number are infinity. Reynolds number, $Re_{\mathrm{TE}} = V_{\mathrm{TE_{max}}}\, c/\nu$, (where $V_{\mathrm{TE_{max}}}$ is the maximum velocity of trailing edge (TE), ν is the kinematic viscosity of water), range is 1078 to 8625. In this letter we mainly discuss the flow for the case for which the amplitude and frequency of oscillation are nearly in the middle of the parameter range, *viz.*,$\theta_{max} = \pm15^\circ, f = 2$ Hz ($Re_{\mathrm{TE}} = 3234$).

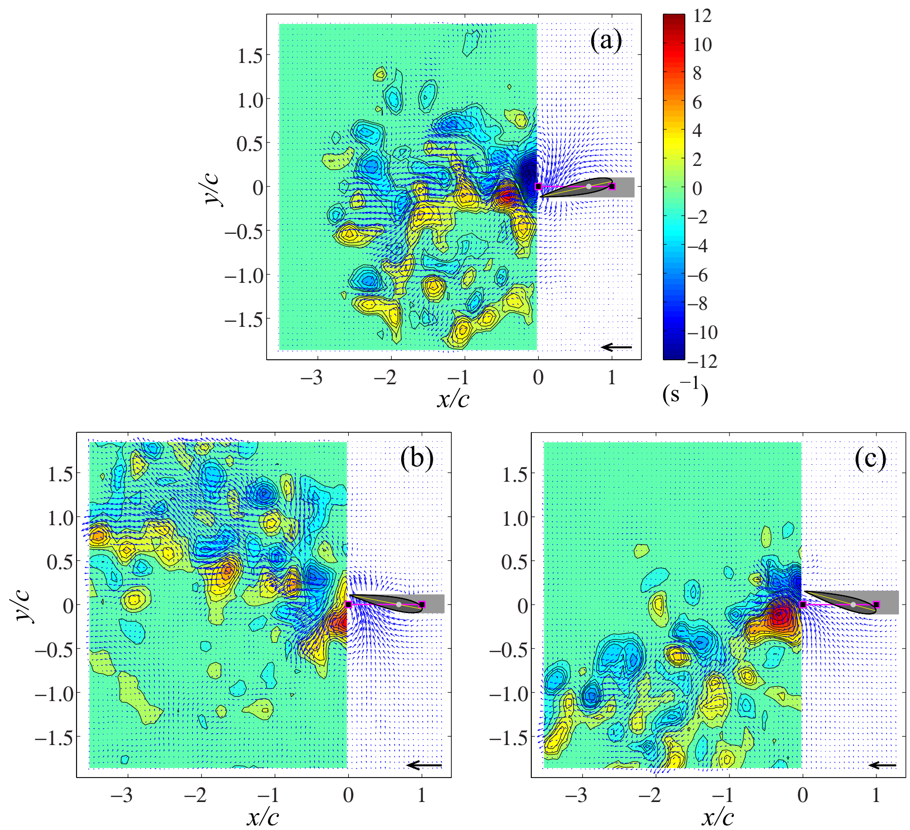

FIG. 2. Instantaneous velocity and vorticity fields ($\theta_{max} = \pm 15°, f = 2$ Hz). Jet is (a) nearly along the center-line (TE moving down, $\theta = -10.2°$), (b) inclined upward (TE moving up, $\theta = +9.2°$), (c) inclined downward (TE moving down, $\theta = +13°$). In all three situations, the flow is like a spread-out jet. Reference vector (bottom-right) shows flow velocity of 150 mm s^{-1}. Negative is the clockwise vorticity and vice versa. Laser sheet is passed from left; grey patch is the shadow.

Figure 2 shows the flow generated in quiescent water by the pitching rigid symmetrical foil. At any instant, the downstream flow is a spread-out, non-coherent jet which may be inclined to the center-line. When the jet is inclined [see Figs. 2(b) and 2(c)], almost entire downstream flow is seen in the one half of the field-of-view, whereas the fluid motion in the other half is negligible. The jet is inclined to the center-line just downstream of the foil. Even though the foil and the pitching motion are symmetric, the flow generated is asymmetric. The vorticity field has irregularly spaced patches without any organized pattern. In contrast, the experiments by Heathcote and Gursul[17] for rigid and flexible foils heaving in still water showed clear vortex pairs (and a vortex jet, though no mention is made about the jet-strength) in the near-wake; however, no information is available about the far-field flow.

Pitching motion induces flow on both sides of the foil chord (see Fig. 2). Particle visualization showed that the fluid motion near the leading edge is very little while relatively large velocities are induced near the trailing edge region; this is seen also in Fig. 2. The dye visualization sequence in Fig. 3 shows that two relatively larger vortices are shed per cycle of oscillation: clockwise when TE moves downward and counterclockwise when TE moves upward; some smaller vortices are also shed (see the supplementary material for dye visualization movie). The vortices, produced due to separation at the trailing edge, are not sustained for long, unlike in the presence of a free-stream flow where they are convected away by the free-stream. In quiescent fluid, there is no agency to convect the vortices away from the place of shedding, and they interact destructively, for instance, as seen in Figs. 3(b) and 3(d).

Observation of the instantaneous flow revealed the following features. When the airfoil starts to oscillate from rest, the flow does not have any specific orientation, but it is spread out. After about

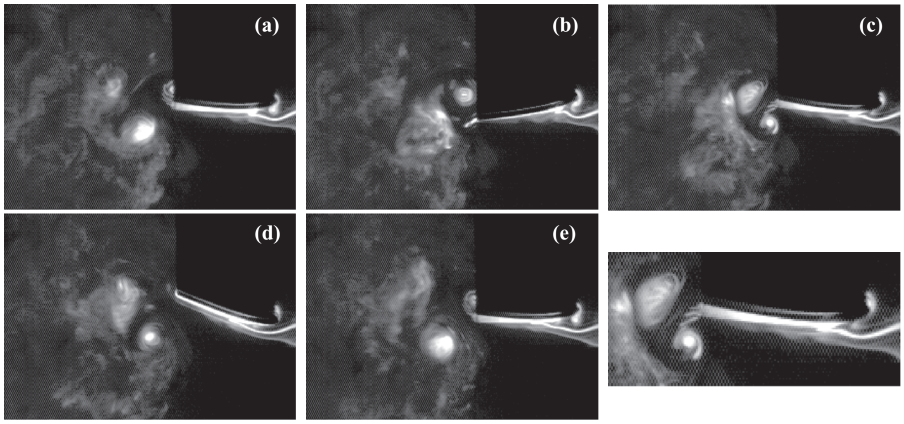

FIG. 3. Dye visualization ($\theta_{max} = \pm 15^{\circ}, f = 2\,\mathrm{Hz}$) when TE is near the (a) mean-position (moving down), (b) bottom-extreme, (c) mean-position (moving up), (d) top-extreme, (e) mean-position (moving down). Laser sheet is passed from bottom. Vortex structures are seen clearly only in the near-wake. Notice the smaller vortices being shed from TE in (c), visible more clearly in the close-up (bottom-right image). Note that, the small 'blob' of dye near leading edge in (a), (b), (e) is not a vortex, but it appears due to two reasons: first, intermittent release of dye from the dye port, and second, since the fluid motion near leading edge is small, the dye accumulates there; the movie (see the supplementary material) clearly shows that the leading edge vortices are not generated. Thus, what appears as a vortex is a 'blob' of dye that is convected by the flow.

10–15 pitching cycles, the flow picks up directionality and inclines to the center-line either upward ["up-mode," e.g., Fig. 2(b)] or downward ["down-mode," e.g., Fig. 2(c)]. Later, the jet changes orientation after arbitrary time intervals, going through the center-line, i.e., the "jet meanders." We studied jet-meandering in detail for two experiments termed as Exp–1 and Exp–2, and the jet-inclination data are presented in Fig. 4; note, the starting conditions and the number of pitching cycles were the same for both experiments. Figure 4 shows that the orientation change is random, for instance, the jet stayed in one particular orientation for periods ranging from 2 to 40 cycles. Also, the choice of jet orientation seems to be independent of the initial conditions.

The random jet-meandering in our experiments is in contrast to the observation by Heathcote and Gursul[17] of quasi-periodic switching in case of rigid as well as flexible foils heaving in still fluid. In their case, the period of switching was two orders higher than the heaving period (typical jet-switching period range was $\sim$ 80–150 heaving cycles). They report the generation of leading edge vortices, but their role in changing the jet orientation is unknown. Although the leading edge vortices are not formed in our experiments (because of the blunt leading edge, pitching-point being close to leading edge ($0.32\,c$), and the zero free-stream velocity (see Fig. 3)), the jet still meanders,

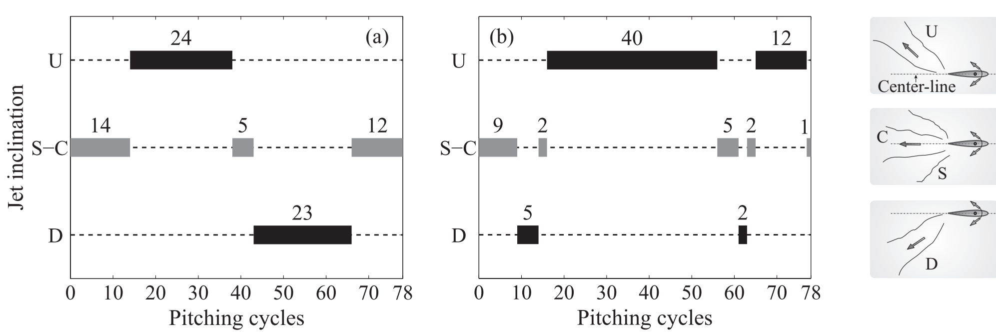

FIG. 4. Jet-inclination data ($\theta_{max} = \pm 15^{\circ}, f = 2\,\mathrm{Hz}$) for (a) Exp–1, (b) Exp–2; U: up-mode, D: down-mode, S–C: jet is spread-out or along the center-line (see schematics). Numbers indicate pitching cycles. Despite the same initial conditions and pitching duration for both experiments, notice that after first few cycles, the jet inclines upward during Exp–1, and downward during Exp–2, and also, the jet meanders across the center-line once during Exp–1, but twice during Exp–2.

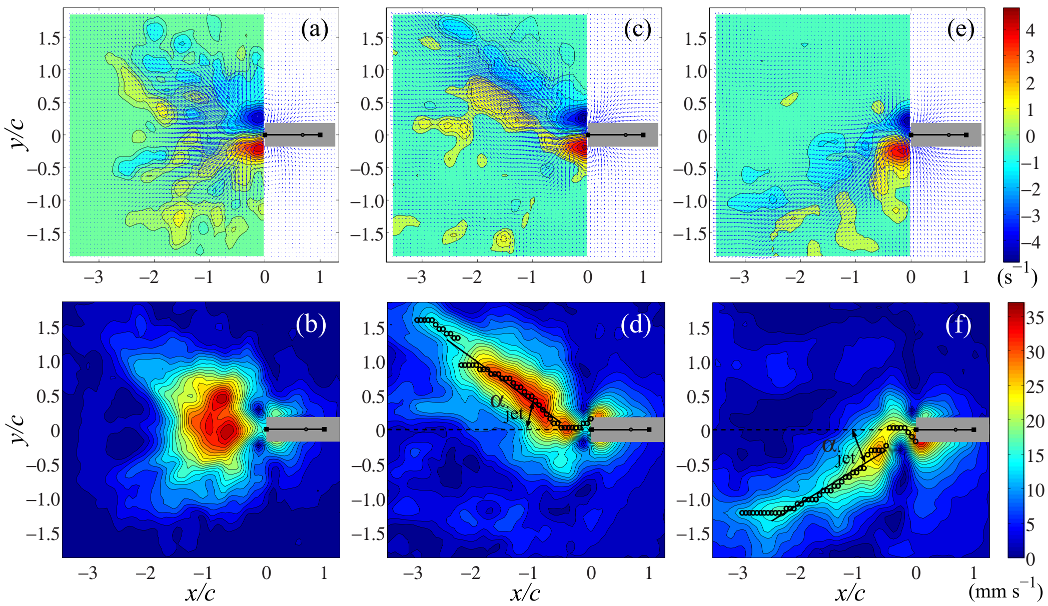

FIG. 5. Conditionally averaged (defined in the text) flow data for Exp–1 (θ_{max} = ±15°, f = 2 Hz); top row – velocity and vorticity fields, bottom row – iso-velocity contours. The flow is averaged for [see Fig. 4(a)] (a) and (b) the first 14 cycles, (c) and (d) up-mode (24 cycles), (e) and (f) down-mode (23 cycles). Rectangular grey patch is the shadowed region; shadow-width indicates the y-amplitude of TE deflection. In (d) and (f), we show the locations of the maximum velocity (black circles), the linear fit (thick black line), and the jet-inclination angle ($\alpha_{\rm jet}$).

suggesting, leading edge vortices may not be triggering the meandering in this case, and some other mechanism should be at work.

We do "conditional average" of the flow: it is the mean over the duration when the flow is inclined in one particular orientation. Figure 5 shows the conditionally averaged flow; Figs. 5(a) and 5(b) show the flow for the initially spread-out jet, and Figs. 5(c)–5(f) for the inclined jets. The jet-inclination angle ($\alpha_{\rm jet}$) is obtained from the conditionally averaged velocity field (when the flow is inclined for more than 10 cycles) as follows: it is the angle made with the center-line by a straight line fitted to the locations (between $x/c \approx -0.5$ and -2.5) of maximum velocity [see Figs. 5(d) and 5(f)]; $\alpha_{\rm jet}$ is positive for up-mode and negative for down-mode. For Exp–1, $\alpha_{\rm jet} \approx +32^\circ$ and -27°; for Exp–2, $\alpha_{\rm jet} \approx +24^\circ$, $+28^\circ$ (up-mode). When the flow is inclined only for a few cycles (e.g., 2 and 5 cycles in Exp–2, down-mode), conditional average is not meaningful. These angles are comparable to those reported in Heathcote and Gursul[17] for heaving foils ($\sim 25^\circ - 30^\circ$).

To get the long time mean of the flow we average over 130 pitching cycles. The mean vorticity field shown in Fig. 6(a) consists of (on the average) two counter-rotating vortices near TE. Figure 6(b) shows a 'weak' jet that appears to move in the inclined-upward direction; however, a long enough time average over many more cycles would produce symmetric velocity profiles at all downstream locations. The maximum velocity in the jet ($\overline{u}_{\rm max}/V_{\rm TE_{max}} = 0.3$) is attained at $x/c = -0.46$.

The flow is studied for 12 cases; the number of pitching cycles for the cases with $f = 1, 2, 3, 4$ Hz were, respectively, 68, 156, 200, 200. In all the cases, the pitching foil produced similar spread-out, inclined, randomly meandering jets.[19] Any general relation between the trends in meandering and the pitching parameters is not evident. The jet-inclination angle is in the range of $\sim 20^\circ$–30° for all 12 cases. The narrow range of $\alpha_{\rm jet}$ across the wide range of pitching amplitudes and frequencies indicates that it is possibly a property of such inclined jets. In all 12 cases, the long term mean showed a divergent, widespread flow.

We have studied the effect of a flexible flap (0.05 mm thick polythene sheet, flexural rigidity (EI) = 3.15 $\times 10^{-7}$ N m^2, 30 mm chord, 100 mm span) appended to the trailing edge of the rigid airfoil. A detailed discussion of flap flexibility is given in Ref. 20. At ±10° amplitude and 1 Hz

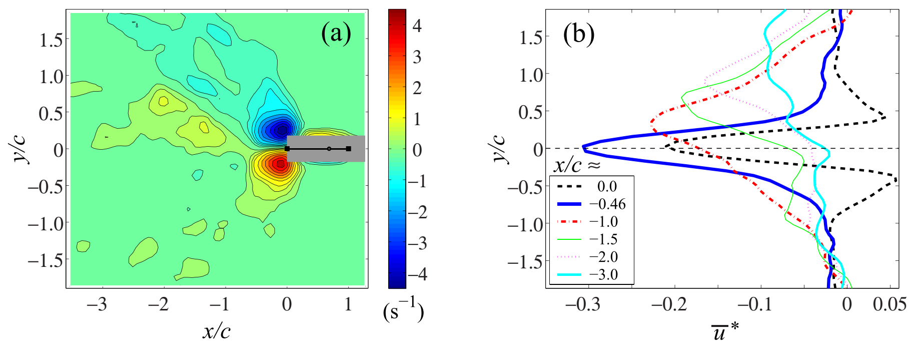

FIG. 6. Mean flow data ($\theta_{max} = \pm 15°, f = 2$ Hz): (a) vorticity field, (b) streamwise velocity profiles normalized by $V_{\mathrm{TE_{max}}}$.

frequency of oscillation when the flap deflection is small, we observed inclined jets as shown in Figs. 7(a) and 7(b), and random meandering as well. But, note the difference that the jet inclines at about two chords downstream of TE, whereas the jet in case of rigid foil inclines just downstream of TE [see Figs. 2(b) and 2(c)]. Interestingly, however, the jet-inclination angle is in the range of $\sim 20°$–$30°$, similar to that for the rigid foil. At higher amplitudes and frequencies of oscillation the flap deflection becomes larger and a coherent, non-meandering jet is generated; the detailed physics of this jet, and the role of flexibility in its generation are reported elsewhere.[20]

We have shown that the flow generated by a rigid symmetric airfoil pitching sinusoidally at a fixed location in quiescent water consists of a weak meandering jet, which we believe has not been reported previously. In the absence of a free-stream flow, the shed vortices do not convect downstream, but interact destructively resulting in spread vorticity instead of any organized vortex pattern. A weak, spread-out jet inclined to the center-line is generated in all 12 cases studied across the Reynolds number range of 1078–8625; jet-orientation is independent of the starting conditions. The jet changes orientation continually and randomly. The random jet-meandering is in contrast to the quasi-periodic jet-switching reported earlier for rigid and flexible foils heaving in quiescent fluid. Appending a flexible flap to the trailing edge of the rigid foil moves downstream the point of jet inclination. The jet-inclination angles are in the narrow range of $\sim 20°$–$30°$ in all 12 cases for the rigid, and for the meandering case of flexible foil, thus suggesting it as a possible property of the inclined jets. None of the studies have detailed upon the mechanism of jet inclination for foils oscillating in quiescent fluid. The reasons for jet inclination and jet meandering need to be studied further.

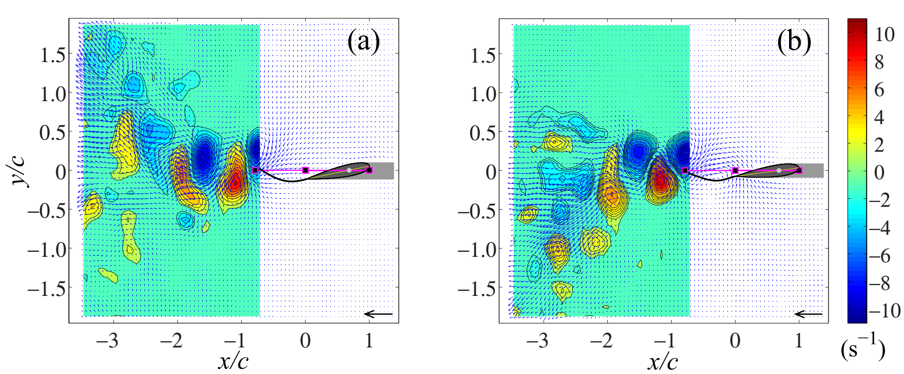

FIG. 7. Instantaneous velocity and vorticity fields for the foil with the flexible flap for $\theta_{max} = \pm 10°, f = 1$ Hz. An undulatory reverse Bénard–Kármán vortex jet is generated. The jet moves along the center-line up to about two chords downstream of TE, and then inclines (a) upward, or (b) downward. Reference vector = 150 mm s^{-1}.

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[18] See supplementary material at http://dx.doi.org/10.1063/1.4800321 for the experimental details, and a movie showing dye visualization in a horizontal plane along the mid-span for the rigid airfoil for the case with $\theta_{max} = \pm 15^{\circ}, f = 2$Hz.
[19] In case of $\theta_{max} = \pm 10^{\circ}, f = 1$Hz, the jet inclined only in one direction. However, the number of pitching cycles (34) was small; a longer duration experiment would probably show meandering.
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