Flexibility in flapping foil suppresses meandering of induced jet in absence of free-stream

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Supplementary Material

1. Introduction

In this Supplementary Material, we provide further details along with one accompanying video to support the conclusions drawn in the main manuscript. In §2 we give the alternative definitions of reduced frequency and Strouhal number based on different length and velocity scales. Section 3 describes the details of the accompanying movie.

2. Alternative definitions of Strouhal number and Reduced frequency

Instead of using free-stream velocity (U_∞), both the Strouhal number and reduced frequency can alternatively be defined using the maximum velocity of the trailing edge (TE) of the rigid foil ($V_{\mathrm{TE_{max}}}$), and either y-amplitude of TE deflection ($\Delta_{\mathrm{TE_{max}}}$) or chord ($c$) as the length scale.

Strouhal number:

1. Using the y-amplitude of TE deflection, the Strouhal number, $St = \frac{f\,\Delta_{\mathrm{TE_{max}}}}{V_{\mathrm{TE_{max}}}}$, turns out to be $\frac{\sin(\theta_{max})}{\pi\,\theta_{max}} \sim \frac{1}{\pi}$ for small θ_{max}.

2. Using chord as the length scale, $St = \frac{f\,c}{V_{\mathrm{TE_{max}}}} = \frac{1}{2\pi\,0.6842\theta_{max}} \sim \frac{1}{\theta_{max}}$.

Reduced frequency:

1. Using the y-amplitude of TE deflection, the reduced frequency, $k = \frac{2\pi f\,\Delta_{\mathrm{TE_{max}}}}{V_{\mathrm{TE_{max}}}}$, turns out to be $\frac{2\sin(\theta_{max})}{\theta_{max}} \sim 2$ for small θ_{max}.

2. Using chord as the length scale, $k = \frac{2\pi f\,c}{V_{\mathrm{TE_{max}}}} = \frac{1}{0.6842\theta_{max}} \sim \frac{1}{\theta_{max}}$.

Defined in the first way, both St and k are constants. Defined in the second way, both St and $k \sim \frac{1}{\theta_{max}}$; but, θ_{max} is already a parameter we have listed.

3. Movie caption

Movie 1.avi – This video shows the dye visualization in a horizontal plane along the mid-span for the airfoil with flexible flap over 10 oscillation cycles (amplitude of oscillation $\theta_{max} = \pm 15°$, and frequency $f = 2\,\mathrm{Hz}$). The rigid airfoil chord is 38 mm and

flexible flap chord is 30 mm. Laser sheet is passed from bottom side of the visualization window. The transparent flap is blackened in the plane of visualization, except for a 3 mm portion near the trailing edge to identify the start of the flap.

Two large vortices, which eventually become part of the 'reverse Bénard–Kármán vortex street', along with a few smaller vortices are shed per oscillation cycle. Movie clearly shows the role of flexible flap in the formation of non-meandering unidirectional vortex jet aligned along the center-line. The vortices are shed at the appropriate space and appropriate phase of the cycle. Note also that a vortex once shed is pushed downstream by flap induced motion. The movement of a streak of dye present below the airfoil clearly shows the pulling of the fluid towards the airfoil and the flap.

Note that, the movie clearly shows that the leading edge vortices are not generated by the pitching foil. The small 'blobs' of dye near the leading edge and also on the airfoil surface are not the vortices, but they are formed due to the following two reasons: one, intermittent release of dye from the dye port, and two, since the motion of fluid is small near the leading edge, the dye accumulates there. These 'blobs' of dye are eventually convected downstream by the flow.

Similar dye visualization movie for the rigid foil without flexible flap is published as Supplementary Material with Shinde & Arakeri (2013).

REFERENCES

SHINDE, S. Y. & ARAKERI, J. H. 2013 Jet meandering by a foil pitching in quiescent fluid. *Phys. Fluids* **25**, 041701.