Numerical simulations of vortex-induced vibration of an airfoil by vortex method

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Abstract

The unsteady, incompressible, viscous flow over a NACA0012 airfoil with two degrees of translational freedom undergoing vortex-induced vibration is simulated numerically. The motion of the airfoil is modeled by a spring-damper-mass system and the Reynolds number is kept at 200. It turns out to be a self-limiting process, and trajectory of the center of the airfoil chord is “figure 0” shape. Factors, such as frequency ratio, mass ratio and angle of attack, are investigated and all influence force coefficients and displacements in both x and y directions by different tendency. A forcing frequency equal to 2.5 times the natural one produces higher lift-to-drag ratio and lower fluctuation than other forcing frequencies.

Fluid-structure interactions occur in many engineering field, such as ocean engineering, vehicle engineering and wind engineering. These interactions give rise to complicated structural vibration and could cause structural damage and fracture under certain unfavorable conditions. As a result, it is important to research vortex-induced vibration for the design and check of a variety of engineering structures.

Vortex method is adopted here and its governing equations are vorticity dynamics equation and continuity equation.

$$\frac{\partial \omega}{\partial t} + (\mathbf{u} \cdot \nabla)\omega = \nu \nabla^2 \omega \tag{1}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{2}$$

In order to validate the accuracy of the program, two applications are shown in this paper. Results of circular cylinder undergoing harmonic oscillation and flapping wing simulated as flight of Drosophila melanogaster show good agreement with reference data.

Simulation of vortex-induced vibration of the NACA0012 airfoil is described by the equation

$$2\pi \mathrm{St}^* M^* \frac{\mathrm{d}^2 \boldsymbol{\psi}}{\mathrm{d}\tau^2} + Sg \cdot fr \frac{\mathrm{d}\boldsymbol{\psi}}{\mathrm{d}\tau} + 8\pi^3 \mathrm{St}^{*3}\ fr^2 M^* \boldsymbol{\psi} = \mathbf{C}_f \pi \mathrm{St}^* \tag{3}$$

In the equation, St* is the Strouhal number of the airfoil when the airfoil is static and defined as $\mathrm{St}^*=f_s^* c/|\mathbf{u}_0|$, f_s^* is the vortex shedding frequency of the airfoil when it is static, c is airfoil chord, $|\mathbf{u}_0|$ is potential velocity. M^* is mass ratio of the airfoil to the air where the airfoil occupies. Sg is damping factor and $Sg=8\pi^2\alpha \mathrm{St}^{*2} M^*$, frequency ratio $f_r=f_n/f_s^*$, $\mathbf{C}_f$ is force coefficient vector and $\mathbf{C}_f=2\mathbf{F}(t)/\rho c|\mathbf{u}_0|^2$.

Figure 1 shows the self-limiting process of VIV NACA0012 airfoil for different damping factor Sg when frequency ratio f_r=1.0. The trajectories are "figure 0" shape, and amplitude of the vibration appears to remain same as Sg increases from 0.01 to 0.1. However, when Sg increases to 10.0, the amplitude decreases sharply.

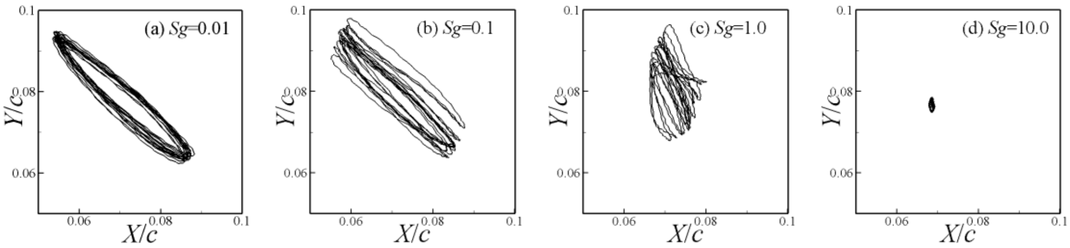

Figure 1 X-Y phase plot, NACA 0012 airfoil, Re=200, M^*=1.0, f_r=1.0

Vortex-induced vibrating NACA0012 airfoil is nonlinear. Forces change airfoil's velocity and position and in turn, airfoil's new position will produce different induced forces and structural response. Results of different damping factor *Sg*, mass ratio M^* and angle of attack *AOA* are shown.

While M^* and *AOA* are invariably equal to 1.0 and 30 respectively, mean of drag coefficient $C_{d\mathrm{mean}}$ are slightly different when damping factor is less than 10.0 for the same frequency ratio. It shows that damping factor has less influence on $C_{d\mathrm{mean}}$. *AOA* has obvious influence when *Sg* and M^* are invariable, that is, the bigger AOA is, the bigger $C_{d\mathrm{mean}}$ is. Impact of M^* shows that with smaller M^*, $C_{d\mathrm{mean}}$ is bigger overall.

Results show that *Sg* has little impact on average value of displacement in x direction X_{mean}. For different *AOA*, the bigger the *AOA* is, the bigger the X_{mean} is. That's because the bigger the *AOA* is, the bigger the $C_{d\mathrm{mean}}$ is, and also greater acting force on the airfoil. The impact of M^* on X_{mean} is: the bigger the M^* is, the smaller the $C_{d\mathrm{mean}}$ is, that's because relatively small ψ will be got in equation (3) as the initial condition is same and relatively big M^* be chosen.

Root-mean-square value of displacement in x direction X_{rms} is also shown. When frequency ratio f_r is 1.0, very big X_{rms} value has been got, indicating that resonance occurs. Away from resonant frequency, X_{rms} decreases sharply, especially when f_r increases to 3.0. *Sg* and M^* have the same impact on X_{rms}, that is bigger *Sg* and M^* produce smaller X_{rms}. However, influence of *AOA* is opposite.

Figure 2 shows the ratio C_l/C_d (standing for $C_{l\mathrm{mean}}/C_{d\mathrm{mean}}$) is maximum when f_r equals to 2.5 in the whole f_r range, and relatively small values of X_{mean} and X_{rms} are also got while f_r=2.5 in former section. That is, when the external excitation frequency is two and a half times the natural one of the airfoil, it will acquire relatively higher lift-to-drag ratio and lower fluctuation.

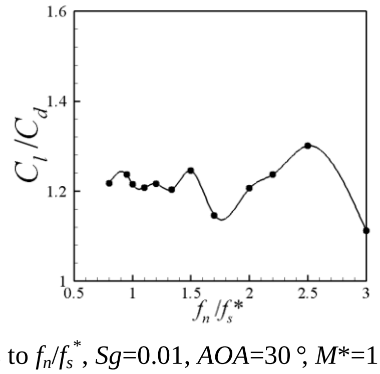

Figure 2 $C_{l\mathrm{mean}}/C_{d\mathrm{mean}}$ versus to f_n/f_s^*, *Sg*=0.01, *AOA*=30°, M^*=1.0, NACA0012, Re=200

We also investigate the aeroacoustic noise caused by vortex-induced vibration of NACA0012 airfoil and will present them later.

Keywords: vortex-induced vibration; airfoil; unsteady flow; aeroacoustic noise