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Suppression mechanism of two-degree-of-freedom vortex-induced vibration by Lorentz forces in the uniform flow

Hui Zhang*, Meng-ke Liu, Yang Han, Ming-yue Gui, Jian Li, Zhi-hua Chen

Science and Technology on Transient Physics Laboratory, Nanjing University of Science and Technology, Nanjing 210094, China

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ABSTRACT

In this paper, the control of 2DOF VIV (two-degree-of-freedom vortex-induced vibration) by Lorentz force has been investigated numerically based on the derivation of stream function-vorticity equations together with the initial and boundary conditions in exponential-polar coordinates attached on a moving cylinder, hydrodynamics forces and the cylinder motion equation. From the derivations of force components, the lift/drag induced by the inertial force only depend on the motion along the corresponding direction, while the lift/drag induced by flow field is affected by the cylinder motion along the two directions. Based on the calculation results, the displacement variation of 2DOF VIV along the transverse direction is similar with that of 1DOF VIV (one-degree-of-freedom vortex-induced vibration). However, the secondary vortex is strengthened with the effect of the pressure side and weakened with the effect of the suction side. With the application of symmetrical Lorentz force, the effects of the pressure/suction side and vortex shedding are weakened, which lead to the suppression of 2DOF VIV. Moreover, the cylinder vibration is fully suppressed and the drag is negative due to the net thrust generated if Lorentz force is large enough, which means the final position of cylinder is at the upstream of the initial position. Furthermore, the fluid-structure interactions from the quiescent cylinder to the steady vibration and then vibration control by Lorentz force are investigated. The shear layers and secondary vortexes grow with the increase of cylinder amplitude and decay with the decrease of cylinder amplitude due to the suppression of cylinder vibration controlled by Lorentz force in the whole process.

1. Introduction

Fluid-structure interactions occur in many engineering fields. Under unfavorable conditions, structural damage can occur when the interactions give rise to complicated vibrations of the structures. The fluctuating forces induced by changing vortex shedding cause vibration of the cylinder when the cylinder is mounted on flexible supports. Subsequently, the flow field is altered by the vibrating cylinder and then the flow-induced force changes. Increases in the vibration of the cylinder may occur until limiting behavior is reached. VIV is a fundamental and revealing problem.

At early stage of studies on VIV, the fully coupled problem involved in VIV has been investigated with various numerical treatments. These treatments can be categorized into two broad groups. In one group, Navier–Stokes equations were solved directly; for example, with direct numerical simulation [1–3], the spectral element spatial method [4,5] or the finite element method [6–8]. In the other group, solving the vorticity transport equations determined the flow field. In this method, the usual assumption is a two-dimensional laminar flow, as with the vortex-in-cell (VIC) method [9,10] or the viscous-vortex method [11,12]. Previous studies have shown that the response was often essentially sinusoidal. In these studies, the lock-in phenomenon was considered. The vortex-induced vibrations with a circular cylinder as well as associated phenomena, such as the unsteady lift and drag on the cylinder, the response of the cylinder, the vortex shedding frequency and the cylinder motion effects on the vortex structure in the wake were assessed.

Vortex-formation modes have been examined later [13,14]. Vorticity measurements exhibit the 2S, 2P and P+S modes, as well as a regime in which the vortex formation was not synchronized with the body vibration. The regimes of fluid forcing and vortex-formation modes can be identified. They ascertained conditions at which the fluid forcing showed qualitative abrupt jumps, as amplitude or frequency was varied, similar to the jumps found in the "amplitude cuts" of previous studies.

By recent research, Franzini et al. [15], Lam and Zou [16], Korkischko and Meneghini [17] looked at the interactions with multi-

* Corresponding author.
E-mail address: zhanghui1902@hotmail.com (H. Zhang).

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ple cylinders. These studies showed that the arrangement or gap had a significant effect on the VIV system responses. Professor Zhou's group investigated the different cases of fluid-structure interactions as a cylinder in planar shear flow [18], two cylinders in tandem with shear flow [19], three cylinders in equilateral arrangements [20], four square-arranged cylinders [21], two-degree-of-freedom (2DOF) VIV on isolated and tandem cylinders with varying natural frequency ratios [22] and etc.

However, the control of VIV has many practical applications in the engineering point of view. A large fluctuation of drag and lift forces, the increase of drag, acoustic noise and even structure damage are usually generated by the undesirable flow separations and vibrations of the body. It is expected that the above phenomenon are suppressed in the process. The phenomena can be suppressed by applying modern flow control methods and technologies [16,23–26].

The Lorentz force was employed to control cylinder wake flow successfully in the 60 s of last century, and this type of forcing has attracted new attention in last few years due to its potential applications in engineering situations. The electro-magnetic control was considered as one of the most practical methods to manipulate the flow [27–30]. The effects of the Lorentz force on the elimination of flow separation were investigated numerically by Crawford and Karniadakis [31] to assess flow past a fixed circular cylinder. The suppressing effect of the Lorentz force was confirmed by Weier et al. [32] using both experimentations and calculations. Kim and Lee [33], Posdziech and Grundmann [34] showed that both pulsed and continuous Lorentz forces could suppress the lift oscillation and stabilize the flow. Both optimal and closed-loop control methods were developed to improve control efficiency of the cylinder wake [35–37], and the one-degree-of-freedom (1DOF) VIV of the shear incoming flow [38] together with control of 1DOF VIV [39] were investigated preliminary in our research group.

It is clear that the investigation of fluid-structure interactions as a fully coupled problem is far from complete in 2DOF VIV especially in control of 2DOF VIV by Lorentz force, such as the effects of the secondary vortexes along the streamwise directions, including the distinct control mechanisms of 2DOF VIV by Lorentz force along the transverse and streamwise directions. Moreover, the forces and response of cylinder are considered as the sinusoidal function approximately in the previous studies, which is difficult to deal with the whole process from the quiescent cylinder to steady vibration and then vibration control. Therefore, more in-depth investigations are necessary.

In this paper, the exponential-polar coordinate attached to the moving cylinder was used to deduce the stream function-vorticity equations of 2DOF VIV, the initial and boundary conditions together with distribution of hydrodynamic force which is composed of the vortex-induced force, inertial force and viscous damping force. The fluid-structure interactions from the quiescent cylinder to steady vibration and then to vibration control were investigated numerically. In addition, the variations of flow field, pressure, lift/drag and cylinder displacement before and after control were discussed. The distinct mechanisms of 2DOF VIV along the streamwise and transverse directions controlled by Lorentz force were revealed.

2. Governing equations

Alternating streamwise electrodes and magnets are mounted on the two halves of the cylinder surface for control of VIV. In this way, the electromagnetic body force (Lorentz force) $\mathbf{F}^*$ can be a dimensionless form [32,40].

$$\mathbf{F}^* = N\mathbf{F}$$

with

$$\begin{aligned} F_r &= 0 \\ F_\theta &= e^{-\alpha(r-1)} g(\theta) \text{ with } g(\theta) \\ &= \begin{cases} 1 & covered\ with\ actuator\ on\ upper\ surface \\ -1 & covered\ with\ actuator\ on\ lower\ surface \\ 0 & elsewhere \end{cases} \end{aligned} \quad (1)$$

where r and θ are polar coordinates, subscripts r and θ represent the components in r and θ directions, respectively. α is a constant, representing the effective depth of Lorentz force in the fluid [32,40]. The interaction parameter is defined as $N = \frac{j_0 B_0 a}{\rho u_\infty^2}$, with the current density j_0, B_0 the magnetic field and a the cylinder radius.

Introducing the exponential-polar coordinates system (ξ, η) defined as $r = e^{2\pi\xi}$, $\theta = 2\pi\eta$, the dimensionless stream function-vorticity equations describing the flow with an applied Lorentz force in a coordinate system attached on the moving cylinder, are written as [38,39]

$$H\frac{\partial \Omega}{\partial t} + \frac{\partial (U_r\Omega)}{\partial \xi} + \frac{\partial (U_\theta\Omega)}{\partial \eta} = \frac{2}{\mathrm{Re}}\left(\frac{\partial^2\Omega}{\partial \xi^2} + \frac{\partial^2\Omega}{\partial \eta^2}\right) + NH^{\frac{1}{2}}\left(\frac{\partial F_\theta}{\partial \xi} + 2\pi F_\theta - \frac{\partial F_r}{\partial \eta}\right) \quad (2)$$

$$\frac{\partial^2\psi}{\partial \xi^2} + \frac{\partial^2\psi}{\partial \eta^2} = -H\Omega \quad (3)$$

where the stream function ψ is given by $\frac{\partial\psi}{\partial\eta} = U_r = H^{\frac{1}{2}}u_r$, $-\frac{\partial\psi}{\partial\xi} = U_\theta = H^{\frac{1}{2}}u_\theta$, and $H = 4\pi^2 e^{4\pi\xi}$, and the vorticity is defined as $\Omega = \frac{1}{H}(\frac{\partial U_\theta}{\partial \xi} - \frac{\partial U_r}{\partial \eta})$, where u_r and u_θ are the velocity components in the r and θ directions, respectively. Furthermore, $\mathrm{Re} = \frac{2u_\infty a}{\nu}$, where u_∞ is the free-stream velocity, a is the cylinder radius, ν is the kinematic viscosity, and $t = \frac{t^* u_\infty}{a}$ is the non-dimensional time, with t^* representing the dimensional time.

Under the effect of the vortices, the cylinder vibrates when the constraint is released. According to the Galilean velocity decomposition and the stream function definition, we have

$$\psi = \psi' - \frac{dl_x}{dt}e^{2\pi\xi}\sin(2\pi\eta) - \frac{dl_y}{dt}e^{2\pi\xi}\cos(2\pi\eta) \quad (4)$$

where the superscript "′" represents the absolute coordinate, and the absence of a superscript denotes the coordinate fixed on the cylinder moving with the velocities $\frac{dl_x}{dt}$ and $\frac{dl_y}{dt}$ in the streamwise and transverse directions, respectively. l_x and l_y are the dimensionless cylinder displacements in the streamwise and transverse directions, respectively.

Then, we have

$$\begin{aligned} -\frac{1}{H}\frac{\partial^2\psi}{\partial\xi^2} &= -\frac{1}{H}\frac{\partial^2\psi'}{\partial\xi^2} + \frac{dl_x}{dt}e^{-2\pi\xi}\sin(2\pi\eta) + \frac{dl_y}{dt}e^{-2\pi\xi}\cos(2\pi\eta) \\ -\frac{1}{H}\frac{\partial^2\psi}{\partial\eta^2} &= -\frac{1}{H}\frac{\partial^2\psi'}{\partial\eta^2} - \frac{dl_x}{dt}e^{-2\pi\xi}\sin(2\pi\eta) - \frac{dl_y}{dt}e^{-2\pi\xi}\cos(2\pi\eta) \end{aligned} \quad (5)$$

and $\Omega' = -\frac{1}{H}\left(\frac{\partial^2\psi'}{\partial\xi^2} + \frac{\partial^2\psi'}{\partial\eta^2}\right) = -\frac{1}{H}\left(\frac{\partial^2\psi}{\partial\xi^2} + \frac{\partial^2\psi}{\partial\eta^2}\right) = \Omega.$ (6)

3. Hydrodynamic forces

Defining the net hydrodynamic force $\mathbb{F}^\theta$ exerted on the cylinder in the dimensionless form

$$C_F^\theta = \frac{\mathbb{F}^\theta}{\rho u_\infty^2/2} = \sqrt{(C_\tau^\theta)^2 + (C_p^\theta)^2}.$$