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# Numerical investigation of the vortex-induced vibration of an elliptic cylinder free-to-rotate about its center

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## HIGHLIGHTS

- The vibration and rotation of an elliptic cylinder are considered simultaneously.
- Large torsional friction leads to no rotation while small friction results in galloping.
- The elliptic cylinder undergoes unstable rotation at small reduced velocities.
- The amplitude of rotatable cylinder is larger than that of non-rotatable one.
- Rotation response is determined by friction, torque and flow field around the cylinder.

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## ABSTRACT

Vortex-induced vibration (VIV) of an elliptic cylinder free to rotate about its center is numerical studied at Reynolds number 2580≤Re≤15490. The vibration and rotation responses occurring simultaneously are considered with normalized torsional friction varied from $3.34\times10^{-4}$ to 1.17. A two-way fluid–structure interaction (FSI) approach is used to solve the incompressible flow equations and the structure motion including the vibration and rotation in two dimensions. The numerical results indicate that the torsional friction is a key factor, determining the rotation response and then affecting the vibration amplitude. When the torsional friction is too large or the reduced velocity is too small, the elliptic cylinder is unable to rotate, while too small friction leads to transverse galloping instead of the desynchronized region. For the elliptic cylinder with moderate frictions, the response occurs similar as the circular cylinder, but the amplitude in the desynchronized region is larger than the circular cylinder due to the hydrodynamic instability. The results show four kinds of rotation response, which are associated with the time-averaged torque and the flow field around the elliptic cylinder. Compared to the non-rotatable elliptic cylinder with 0° attack angle, the rotatable cylinder vibrates more vigorously.


## 1. Introduction

Flow over bluff bodies is omnipresent in nature and engineering applications. Alternative vortex shedding occurs in the wake even at very low Reynolds number, resulting in unsteady hydrodynamic forces and hence the structural oscillation, called vortex-induced vibration (VIV). Extensive efforts have been dedicated to developing various VIV control techniques,

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including active control (Chen et al., 2013, 2015a; Choi et al., 2002; Zhu et al., 2015) and passive control (Lee et al., 2014; Khorasanchi and Huang, 2014; Zhu and Yao, 2015).

Among them, fairing is a classical and effective device to minimize vibration by preventing the interaction of shear layers with the near wake. Chen et al. (2015b) experimentally investigated the control effectiveness of fairing passive jets around a circular cylinder, which achieved 33.7% in drag reduction. Wang et al. (2015) reported 26%–31% drag reduction was obtained by a waterdrop-shaped fairing. As the attack angle varies over time in practice, fairings should be free to rotate to align themselves with the flow in time (Xie et al., 2015). Assi et al. (2014b) investigated the VIV suppression of a rotatable short-tail fairing and found that the torsional friction was a critical factor determining the effectiveness. The effect of torsional friction was first performed by Assi et al. (2009) investigating the stability of a free-to-rote splitter plate. In our recent study (Zhu et al., 2017), we found a high enough friction was required to hold a triangular fairing in a stable position. Yu et al. (2015) investigated the effect of rotational friction on the stabilization of a U-shaped fairing at Re = 100–1000. Xie et al. (2015) extended the study to higher Reynolds numbers. From their numerical results, it was observed that the U-shaped fairing was able to suppress vibration and reduce drag force effectively at a higher friction, while it underwent a vigorous oscillation at smaller frictions. Law and Jaiman (2017) introduced a C-shaped foil attached at the end of a splitter plate behind a circular cylinder, which has a similar performance as the U-shaped fairing with respect to the VIV suppression.

As elliptic profile is more streamlined than circular profile, elliptic fairings may be a good choice for VIV suppression. A circular cylinder with an elliptic fairing could be seemed as an elliptic cylinder, whose vibration has been investigated by some researchers. The flow around an elliptic cylinder with its minor to major axis ratio ranged from 0.3 to 1 has been studied by Faruquee et al. (2007) at Re = 40. Navrose et al. (2014) numerically investigated the VIV of an elliptic cylinder in the laminar flow regime, $60 \leq Re \leq 140$. In the numerical study by Kim et al. (2016), a helically twisted elliptic cylinder was observed to reduce flow drag by 23% at Re = 3900. Kumar et al. (2018) found an elliptic cylinder as a streamlined object leaded to significant alterations in the construction and appearance of resonance branches at Re = 100. Nevertheless, up to now, the rotation of elliptic cylinder has not been considered.

The aim of this work is to investigate the VIV of an elliptic cylinder that is free to rotate about its center and traverse in two other directions. The effects of the torsional friction for the ellipse rotating about its center and incoming flow speed are numerically examined using a two-way fluid–structure interaction (FSI) approach, as it is expensive to conduct experimental evaluation and difficult to determine the torsional friction in experiments.

## 2. Problem description

As shown in Fig. 1, a rigid, spring mounted elliptic cylinder is considered in this work with the ratio of its minor axis (1.15 *D*, *D* is the diameter of a baseline circular cylinder) to major axis (2.3 *D*) of 0.5. The ellipse is free to rotate about its center and free to vibrate in both streamwise and transverse directions with Reynolds number ranging from 2580 to 15490. The vibration and rotation are considered simultaneously, making the issue more complicated, and it is time-consuming to conduct three-dimensional (3D) simulations at this moderate Reynolds number range. Therefore, two-dimensional (2D) simulations are employed to gain some insights on such a complicated issue while keeping the computational model simple. The 2D results are useful to understand some flow physics in the plane, and bear similarity to but cannot be directly extrapolated to 3D results as the three-dimensional effect is neglected in this work. This preliminary 2D investigation may provide some reference for the further 3D study. Table 1 lists the key parameters for simulation. A circular cylinder is considered as a baseline case for comparison. Additionally, a non-rotatable elliptic cylinder with attack angles of $\theta = 0°$ and $\theta = 90°$ is also compared in this work. The reduced velocity is defined as $U_r = u_{in}/f_n D$ ranging from 2 to 11, where $u_{in}$ is the free-stream velocity.

As depicted in Fig. 1, the computational domain is a rectangle region with size of 172.5 *D* (in the streamwise direction) × 69 *D* (in the transverse direction). Thus the blockage ratio is below 2%. The inlet boundary is 34.5 *D* away from the cylinder center, imposed with a uniform steady flow ($u = u_{in}$ and $v = 0$, where $u$ and $v$ are the velocity components in $x$ and $y$ directions, respectively). At the outlet, a zero gradient condition is specified for the flow velocity ($\partial u/\partial x = 0$ and $\partial v/\partial x = 0$). The two lateral boundaries, defined as slip walls ($\partial u/\partial y = 0$ and $v = 0$), are 34.5 *D* away from and parallel to the $x$ -axis. No-slip wall condition is implemented on the elliptic cylinder surface. At the initial time, the major axis of the free-to-rotate elliptic cylinder is parallel to the flow direction, i.e. the attack angle is $\theta = 0°$.

As shown in Fig. 1, in order to improve the efficiency of mesh update, the computational domain is divided into three zones: an accompanying moving zone, a dynamic mesh zone and a static mesh zone. The accompanying moving zone is a circle with diameter of 3.45 *D*, following the translational and rotational motion of the elliptic cylinder. The dynamic mesh zone is a square with edge of 34.5 *D*, performing mesh adaptation in time. Calculation data is timely transferred between the overlapping interfaces of the accompanying moving zone and the dynamic mesh zone. Moreover, slip motion is allowed between the two interfaces so that the rotation of the accompanying moving zone does not cause any mesh stretching of the dynamic mesh zone, whose mesh update only depends on the translational motion. The rest of the computational domain is set as a static mesh zone, whose mesh is unchanged in simulations.

## 3. Mathematical model and numerical approach

### 3.1. Governing equations

The governing equations for fluid flow are the 2D unsteady Reynolds-averaged-Navier–Stokes (URANS) equations with a shear stress transport (SST) $k$-$\omega$ turbulence model. The incompressible URANS equations consist of mass and momentum