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CFD analysis of energy harvesting from flow induced vibration of a circular cylinder with an attached free-to-rotate pentagram impeller

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HIGHLIGHTS

- A new device is proposed to harness energy from vibration and rotation simultaneously.
- Vibration of a cylinder with a pentagram impeller is studied at high Reynolds number.
- Effect of torsional friction on vibration response and mechanical power are examined.
- The rotation of impeller leads to a hydrodynamic instability at high reduced velocity.
- Effect of additional damping on the system dynamics and harvested power are studied.

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ABSTRACT

A new converter consisting of an elastically mounted circular cylinder and a free-to-rate pentagram impeller is proposed to harness hydrokinetic energy from water currents. The vibration energy of the cylinder and the rotation energy of the impeller are harvested simultaneously. The two-way fluid-structure interaction simulations are employed to investigate the vibration and rotation response of the converter. The simulated Reynolds number range is $14{,}000 < Re < 80{,}000$, falling in the TrSL2 (transition of shear layer 2) and TrSL3 regimes. The results indicate that the vibration amplitude of the converter increases with increasing of the flow velocity, and the growth becomes faster at high reduced velocity (U_r). The presence and rotation of the impeller contribute to the hydrodynamic instability of the system at $U_r \geq 9$, where the rotational direction is constantly changing. The hydrodynamic instability brings about a wider flow wake and unstable vortex shedding, resulting in the enhancement of vibration and the increase of power. For such a rotation symmetric structure, increasing the torsional friction does not play a significant role in suppressing the hydrodynamic instability. The estimated power generating capacity is sensitive to flow velocity and additional damping ratio. The average power efficiency is about 22.6%, and the power density for a $5D \times 5D$ staggered configuration with ζ_{harn} of 0.031374 can reach 885.53 W/m^3.

1. Introduction

Capturing the renewable energy from ocean has been a hot issue for its significant advantages of sustainable, cheap, abundant and clean [1–3]. In the last few decades, wave, tide and current energy harvesting technologies are developed rapidly and some of them have huge potential for power generation [4–7]. Specific floats, buoys or pitching devices and turbines are usually adopted to convert the power of waves and currents into clean and pollution-free electricity [8,9]. However, large-diameter sharp rotor blades may threaten marine life and livelihoods linked to fisheries. Additionally, the installation and maintenance charges of such blades are high, and enough flow speed is required to drive them. The vast majority of currents are slower than 1.5 m/s [10,11] while most of marine turbines are financially viable in average flow speeds of 2.5–3.6 m/s or higher [12–14].

Bladeless turbines harvesting energy from flow induced vibration (FIV) have been proposed in the last decade with the help of a rotary generator [15], magnets [16] or piezoelectric materials [17]. FIV is a typical fluid-structure interaction (FSI) phenomenon, frequently observed in nature and most practical applications. Bluff bodies exposed to fluid flow perpendicular to their axis usually experience vibration excited by the alternating shedding of vortices in the wake of themselves. The shed vortices create an asymmetric oscillatory pressure distribution, which causes periodic hydrodynamic forces (including

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drag and lift forces) acting on the structure. Then the oscillatory forces lead to the structural vibration called vortex induced vibration (VIV), which is one well-known form of FIV. VIV of circular cylinders have been observed over the entire range of Reynolds number (*Re*) with the exception of $Re < 40$, $200 < Re < 400$ and the transition region from laminar to turbulent flow [18]. An elastically mounted cylinder would be excited to a large-amplitude vibration when it oscillates at or near the natural frequency, called lock-in phenomenon. VIV of a circular cylinder has been studied extensively, especially at low Reynolds number ($Re < 3 \times 10^4$), as summarized in the reviews [19–24]. Galloping is another form of FIV, which is an aero/hydro-elastic instability phenomenon driven by the motion of shear layers on either side of the cylinder [25]. Galloping occurs above a critical flow speed and induces larger amplitude than VIV. Typically, as flow speed increases, VIV occurs firstly, followed by galloping [26]. Since FIV may cause the fatigue damage of structures, it is usually treated as a destructive phenomenon. A great number of efforts have been made to control the vortex shedding and suppress the vibration [27–31]. But from another perspective, FIV is often related to large energy losses, which could be utilized to generate power. Bernitsas and Raghavan [32] invented a hydrokinetic power generating device called VIVACE (vortex induced vibration for aquatic clean energy) converter in 2005, which can harness hydrokinetic energy of currents even as slow as 0.4 m/s [33]. Their team has been successful in utilizing the potentially disastrous phenomenon to harness the power of currents with such a converter [33–36]. The basic unit of the VIVACE converter is a rigid circular cylinder mounted on elastic springs [15], while multiple cylinders in a special array can form a power plant. Mehmood et al. [37] and Abdelkefi et al. [38] examined the energy harvested from VIV of a circular cylinder by attaching a piezoelectric transducer to the transverse degree of freedom. Naseer et al. [39] tried to harvest energy from VIV of circular cylinders by introducing nonlinear attractive magnetic forces. Therefore, elastically mounted circular cylinders, as bladeless turbines, are proposed to convert hydrokinetic energy to mechanical and subsequently electrical energy. Compared with conventional turbines, cylinders can harness energy from slower flows with less negative effect on fisheries, and the cost is significantly less.

From the perspective of energy harnessing, maintaining high vibration response and enhancing the oscillation amplitude of cylinders are favorable. Cylinders with non-circular sections [40] or with attachments (such as a splitter plate) [41,42] could experience galloping that is more vigorous than VIV. Chang et al. [43] and Kim et al. [44] pointed out galloping may be achieved by placing roughness strips on a cylinder's surface, named as passive turbulence control (PTC), which was developed by the Marine Renewable Energy Lab at the University of Michigan to enhance FIV [45–47]. Bokaian and Geoola [48] observed that the proximity of another cylinder could also induce galloping in a circular cylinder. In addition, Sun et al. [26] proposed that increasing the stiffness can bridge the gap between VIV and galloping.

Since both the turbine with blades and the bladeless turbine as a circular cylinder have the capability to generate power, why not combine the two? Certainly, the premise is that the length of the blades is limited as stated above. Therefore, in this paper, a pentagram impeller is designed to harness energy from fluid flow, as shown in Fig. 1. The impeller covers a circular cylinder so that the section becomes non circular and the system stiffness becomes larger. Additionally, the pentagram impeller is free to rotate under the impact of flow. Thus, the vibration energy of the system and the rotation energy of the impeller could be utilized simultaneously to convert more hydrokinetic energy into mechanical energy. The blade length of this impeller is as small as $0.9D$ (D is the diameter of the circular cylinder). Therefore, the cost would not be increased too much compared with the charge of a bare cylinder. A basic unit of this device consists of an elastically mounted rigid circular cylinder and a free-to-rotate pentagram impeller. So here comes the questions, does the rotating impeller affect the vibration response of the system? Is there some mutual influence between the

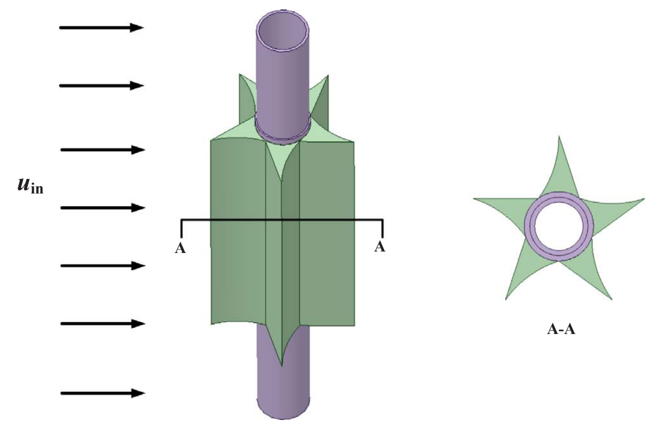

Fig. 1. A new device (a circular cylinder with an attached free-to-rotate pentagram impeller) designed for harvesting renewable energy from water currents.

rotation and the vibration? How much energy can be harvested by this device? Does the energy conversion change the dynamics of the system? The previous literatures are quite limited, and these questions are worth to be investigated before the real applications.

The objective of this paper is to investigate the effect of such a free-to-rotate pentagram impeller on the vibration response of a circular cylinder and examine the power harnessed by this device. The unsteady Reynolds-Averaged Navier-Stokes (URANS) equations coupled with a shear stress transport (SST) k-ω turbulence model are employed to conduct simulations in the range of $14{,}000 < Re < 80{,}000$, which falls in the TrSL2 (transition of shear layer 2, 1×10^3–$2 \times 10^3 < Re < 2 \times 10^4$–$4 \times 10^4$) and TrSL3 (transition of shear layer 3, 2×10^4–$4 \times 10^4 < Re < 1 \times 10^5$–$2 \times 10^5$) regimes [49]. Both the vibration and rotation response are discussed, and the effects of flow velocity, additional damping ratio and rotational friction between the impeller and the cylinder are evaluated.

2. Problem description

The physical model is a mass-spring-damper system with two-degree-of-freedom (2-DOF) as depicted in Fig. 2. The elements of this oscillatory system are a rigid circular cylinder, a pentagram impeller covering the cylinder, two supporting linear springs and the system damping due to friction and energy harnessing. The vibration response of a bare circular cylinder is also considered as a baseline case for comparison. The diameter of the circular cylinder is $D = 38.1$ mm. The pentagram impeller has five even-distributed blades around the cylinder so that the center angle (θ) of each blade is 72°. Each blade has a height of $H = 0.9D$, an arc edge on the left side of radius $R = 1.5D$ and a straight edge on the right side, as shown in Fig. 2(b). Therefore, the hydraulic diameter of the cylinder with a pentagram impeller is $D_{\text{h}} = 26.6$ mm ($D_{\text{h}} = 4A_{\text{i}}/\chi$, where A_{i} is the section area of the system and χ is its wetted perimeter). The impeller is made out of the same material as the circular cylinder so that the mass ratio ($m^* = m/m_{\text{a}} = 6.899$, where m and m_{a} are the mass of the system per unit length and the displaced mass of fluid, respectively) has no change after the installation of the impeller. The natural frequency of the circular cylinder is $f_{\text{n}} = 3.94$ Hz ($f_n = \sqrt{k/(m + m_a)}/2\pi$). When the cylinder is attached by a pentagram impeller, the natural frequency becomes 6.71 Hz due to the increase of stiffness. The damping ratio of the circular cylinder for frictional losses (structural damping ratio) is 0.001456 while it is 0.000406 for the cylinder with an impeller. Besides the structural damping, energy conversion and extraction may add another damping to the system. Three different additional damping ratios (ζ_{harn}) are considered in the simulations to examine the effect on the system dynamics and energy harvesting. The related parameters are listed in Table 1.