Theoretical Analysis of a Novel Tidal Current Energy Converter

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Abstract. Low tidal current velocity can be observed in most coastal areas of China. However, the device suitable for the effective conversion of tidal current energy under low flow velocity, and this conversion is necessary for tidal current energy extraction. This paper proposes a novel tidal current energy converter based on vortex-induced vibration (VIV) and artificial muscles. The converter uses the VIV phenomenon in the flow of the cylinder vibrator to efficiently convert the kinetic energy of the tidal current into the kinetic energy of the moving parts and uses the inverse phenomenon of the electric-motion characteristic of artificial muscles to directly convert the kinetic energy into electrical energy. This paper also discusses the VIV characteristics of the converter's vibrator when connected to nonlinear damping. Theoretical analysis, numerical simulation, and prototype testing were used to determine the influence of various parameters on its hydrodynamic properties and a selection of structural parameters to achieve an optimal performance index. The analysis results showed that the prototype of the converter worked successfully when the flow velocity of the water was in the range of 0.5 m s⁻¹ to 0.75 m s⁻¹.

1. Introduction
China features more than 5,000 kilometers of coastline. Compared with countries possessing the best energy resources, such as Britain and Norway, China’s tidal current energy reserves are characterized by a lower flow velocity and a shallower depth. Since the energy density of a tidal current is directly proportional to the cube of the flow velocity, the development and use of tidal current energy in low-velocity areas will inevitably enlarge the scale of the rotor and increase water depth requirements. Similarly, a sufficient flow velocity is needed (not less than 1.5 m s⁻¹) so that the turbine will work effectively [1]. Therefore, developing a device suitable for effective tidal current energy conversion under low flow velocity is of great need for the extraction of tidal current energy in China. Based on these considerations, this paper proposes a novel tidal current energy converter with artificial muscles (dielectric elastomer material) based on vortex-induced vibration (VIV) theory.

VIV is a common phenomenon of fluid mechanics. As fluid moves past a bluff body, shedding vortices impose periodic forces upon it. In many cases, these forces are strong enough to drive the body oscillating. This phenomenon can be applied to the proposed tidal current energy device. By consciously inducing and enhancing VIV, the kinetic energy of a tidal current can be transformed into the kinetic energy of a vibrating body so as to efficiently convert the tidal current energy. The University of Michigan first proposed a device called Vortex Induced Vibration for Aquatic Clean Energy (VIVACE), which converted the kinetic energy of horizontal flow into the transverse vibration
of its oscillator based on the principle of VIV, and then drove the generator via a mechanical transmission system [2]. Similarly, the Georgia Institute of Technology studied the windward-induced VIV of pendulum sails by driving the deformation of the piezoelectric material at the root of the inverted pendulum to generate the electricity needed to power a wireless device [3].

Some artificial polymers can produce electrostrictive effects while under voltage stimulation (called artificial muscles). Moreover, the electrokinetic characteristics of artificial muscles work in reverse. That is to say, when deformation is generated continuously by an external force, voltage can also be generated continuously. Based on this principle, artificial muscles can be used for power generation [4]. The Stanford International Research Institute developed the ocean wave energy polymer dielectric elastomer generator in 2006. A 40 g dielectric elastomer was shown in testing of the device to produce a maximum energy output of 5.4 J wave$^{-1}$ at a 0.3 Hz vibration frequency, which was enough to provide lighting for ocean buoys [5].

In summary, the artificial muscle tidal current energy converter based on VIV is a novel concept that differs from conventional turbine power generation. VIV can be used to obtain a larger driving force and amplitude at a lower flow velocity. Moreover, artificial muscles can directly convert mechanical energy into electrical energy without the need for a complex transmission mechanism, all through a simple structure with low volume and no noise. The efficient conversion of tidal current energy at a low velocity can therefore be achieved by combining VIV and artificial muscles. This paper gives a detailed description of the theoretical analysis, numerical simulation, and prototype experiments that informed this conclusion.

2. Problem description

The three-dimensional model of the proposed tidal current energy conversion device is shown in figure 1. Figure 2 indicates that the physical model of the device is a typical single-degree-of-freedom mass-spring-damping system. The inlet velocity, vibrator diameter, and damping are all design variables.

![Figure 1. (a) Three-dimensional diagram of experiment rig: 1-oscillator, spring, 3-rail, 4-artificial muscle transduction unit (AMTU), 5-fixed frame; (b) Prototype in test tank.](image)

Two aspects of the damping of the tidal current energy conversion device warrant closer consideration. The first is the system damping of the device itself, which can be obtained through a prototype hydro-static test. The second is the AMTU component. The basic structure of the AMTU is shown in figure 3. The dielectric elastomer comprises VHB4910 polyacrylic acid film and flexible electrodes, which were evenly smeared on its surface and then fixed with circular acrylic rings. For specific relevant contents, refer to Ref. [6]. In order to obtain the device’s mechanical properties, the tensile sensor experimental platform shown in figure 3 was built, the relationship between AMTU force and deformation displacement can be approximated as follows ($x$ indicates the deformation...
displacement of the dielectric elastomer):

\[
F(x) = 8.971 \times 10^{-6} x^3 - 0.001959 x^2 + 0.3441x + 0.1314
\]  

(1)

Figure 2. Physical model and computational domain.

Figure 3. AMTU performance test.

Klamo [7] used the VMEC damping system to analyze the VIV response under various damping conditions and concluded that a change in damping conditions would affect the amplitude and frequency response of VIV. Therefore, the vibration response of a bare circular cylinder was also considered as a baseline for comparison that would be more convenient during the analysis of the vibration response of this converter system.

In light of the existing experimental conditions and the current status of tidal current velocity in northern China, the inlet velocity range was set at 0.4 m s\(^{-1}\) to 0.75 m s\(^{-1}\) for the study. The corresponding Reynolds number interval was 16797<Re<68718, which was in the TrSL3 subcritical Reynolds area [8]. As a nonlinear fluid-structure interaction (FSI) problem, the flow field and the structure field needed to be modeled separately and then calculated as fully coupled. Conducting three-dimensional simulation can be complicated and time-consuming, and prior research has shown that two-dimensional simulation can produce reasonable results [9]. Figure 2 depicts the computational domain for 15D×5D which are needed to ensure the full development of the fluid flowing through the vibrator. The velocity load was set at the entrance, and the initial state of the whole fluid field was consistent with the velocity load. Outflow boundary conditions were assigned in the downstream outlet, and the outer circle of the cylindrical vibrator was set as the FSI boundary condition. Finally, the center of the cylinder, which is equivalent to the damping node, was set as the spring joint.

3. Computational Model and Method

3.1. Motion Model Equation

Many scholars have proposed semi-empirical models for VIV analysis that combine physical model experiments with knowledge of fluid dynamics. In order to correctly express the self-excited and self-
limiting properties of the wake oscillator, this paper establishes a nonlinear motion model equation. The equation incorporates a flow variable to describe various effects of the vortex shedding behind the vibrator. This model can be used to predict the response of the elastic support of the cylindrical vibrator on the Reynolds range of $10^3$-$10^5$.

A control volume model was used to treat the adjacent wake as a nonlinear self-excited oscillator coupled with the engineering structure. The elastic support and viscous damping cylinder equation of motion can be represented as follows:

$$\ddot{y} + 2\xi \omega_y \dot{y} + \omega_y^2 y = a'_i\dot{\omega} + a'_i\dot{U} / D$$  \hspace{1cm} (2)

where $a'_i = \rho D^3 a_i / (m + a_i \rho D^3)$, $i = 3, 4$, $\omega_{y} = \sqrt{k / m / (1 + a_i \rho D^3 / m)}$, $\omega_y$ is the natural angular frequency of the cylinder, $\rho$ is the fluid density, $D$ is the cylinder diameter, and $m$ is the mass per unit length of the cylinder (including the mass of the fluid being propelled). And $\xi_T$ is the total effective damping coefficient, which comprises the viscous structure damping ($\xi$) and the viscous fluid damping ($\xi_f$). $\xi = \left(\xi_1 \sqrt{k / m / \omega_y} + \xi_3\right) / \left(1 + a_i \rho D^3 / m\right)$, $\xi_f = a_i \rho DU / \left(2m\omega_y\right)$, As the structural damping approaches zero, the component caused by the fluid damping limits the amplitude of the vibration.

### 3.2. Solution Method

The motion model equation was calculated and solved using the two-dimensional incompressible unsteady Reynolds-Averaged Navier-Stokes equation and the Spalart-Allmaras turbulence model. The Reynolds average momentum equation can be expressed as follows:

$$\frac{\partial \bar{u}_i}{\partial t} + \rho \left( \frac{\partial \bar{u}_i}{\partial x} + \bar{u}_i \frac{\partial \bar{u}_j}{\partial x_j} \right) = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial \bar{u}_i}{\partial x_j} \right) + \frac{\partial}{\partial x_j} \left( \frac{\partial}{\partial x_j} \mu \frac{\partial \bar{u}_i}{\partial x_j} \right)$$  \hspace{1cm} (3)

where $R_{ij}$ is the Reynolds stress tensor, defined as

$$R_{ij} = u_f \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \frac{2}{3} \rho k \delta_{ij}$$  \hspace{1cm} (4)

and $u$ is the velocity. Similarly, $\rho$ is the pressure, and the subscripts $i$ and $j$ represent the direction of the axis. The Spalart-Allmaras model, widely used in the simulation of cross-flow problems, can be expressed as follows:

$$\frac{\partial}{\partial t} \left( \rho \bar{v} \right) + \frac{\partial}{\partial x_i} \left( \rho \bar{v} u_i \right) = G_i + \frac{1}{\sigma_v} \left[ \frac{\partial}{\partial x_j} \left( \mu + \rho \bar{v} \right) \frac{\partial \bar{v}}{\partial x_j} \right] + C_{v2} \rho \left( \frac{\partial \bar{v}}{\partial x_j} \right)^2 - Y_v + S_v$$  \hspace{1cm} (5)

where $G_v$ is a turbulence-generating item, and $u_f = \rho \bar{v} u_1$ represents turbulent viscosity. The constants used in this model are set as: $C_{v1} = 0.1355$, $C_{v2} = 0.622$, $\sigma_v = 2/3$, $C_{v1} = 7.1$, $C_{v1} = C_{v1} / k^2 + (1 + C_{v2}) / \sigma_v$, and $C_{v2} = 0.3$, $C_{v3} = 2.0$.

### 4. Prototype Experiment

Through theoretical analysis and numerical simulations, the prototype experiment verified the feasibility of the tidal current energy conversion device. The flume experiments were performed at the ocean engineering wave-current lab at The Ocean University of China. Tank size: 30 m × 1 m × 2 m with the maximum water depth of 1m, met the necessary adjustment and control test criteria for the flow velocity of 0.4 m s$^{-1}$ to 0.75 m s$^{-1}$. The prototype of the tidal current energy conversion device was L×B×H: 380 mm × 750 mm × 1420 mm. Figure 1b shows its installation in the water tank.
In order to obtain the natural frequency and the structural damping of the device in the water, a hydrostatic decay test was first performed. Then in the running water experiments, the main variables in the experiment were flow velocity, vibrator diameter, and the AMTU diameter. According to the working conditions described in Section 2, the controlled variable test was carried out successively, and the system vibration data without AMTU was tested as a control group.

5. Results and Discussion

5.1. Vibration Response

Figure 4 shows the relationship of the dimensionless amplitude and the vibration frequency of the proposed tidal current energy converter with reduced velocity $U_r$ under the conditions of a cylinder diameter of 85 mm and an AMTU diameter of 160 mm. A large number of classical experimental studies on the VIV response have demonstrated that the lock-in area of energy capture by VIV can be adjusted by changing structural parameters such as stiffness, mass, damping ratio, and others. Specifically, when the reduced velocity was less than 4, the amplitude value obtained through numerical simulation was very small. The impact of the water on the vibrator was a slight disturbance with no stable rotation formed. When the reduced velocity was greater than 4, the amplitude value increased sharply and remained at a high level. Frequency locking also occurred at this stage.

Compared with results of the numerical simulation, the results of the flume experiment showed less varied characteristics. As reduced velocity increased, vibrating amplitude also increased. The maximum amplitude of the device under the working conditions reached 11 cm, and the transducer unit maintained a good stretching effect without fatigue failure. Observation of the vibration frequency trends of the two groups revealed that they were in agreement and demonstrated stability in the locked range. Moreover, the locked frequency obtained through simulation was relatively stable at around 2 Hz, and the experimental results were stable at around 1.5 Hz. The main reason for the difference between the experimental and simulation results is that numerical simulation is based on physical models, which are idealized for parameters such as friction and damping of system components. To a certain extent, two-dimensional simulation also avoids the three-dimensional effect of fluid.

![Figure 4](image_url)

**Figure 4.** (a) The relationship between the reduced velocity and the dimensionless amplitude; (b) The relationship between reduced velocity and vibration frequency.

5.2. Flow Wake

Figure 5 shows the time history curves of vibration displacement and the wake vortices of the vorticity and velocity contours of the characteristic points in two typical cases. Point A and Point C represent the equilibrium position points in the vibration steady state. The two points are separated by half of a vibration period. However, the vorticity and streamline characteristics are similar, and the spatial distribution is just the opposite. Point B and Point D are the highest and lowest vibration points,
respectively, and their wake traces show the same characteristics as point A and C. This symmetry evolution process reflects the periodicity and approximate symmetry of the displacement curve. The figure reveals that when the dimensionless amplitude was 0.1, there was a clear beat vibration phenomenon in the displacement history curve. This phenomenon was caused by two frequency peaks, which indicate the instability of fluid parameters in the unlocked state.

The vortex-shedding mode of the two states can be summarized as follows: figure 5a represents the 2S shedding mode (two vortices were shed per cycle, one vortex clockwise and the other counterclockwise), figure 5b represents the 2P shedding mode. The vibration amplitudes differed because different vortex shedding modes directly affect the force of the cylinder.

![Figure 5](image)

**Figure 5.** Vibrator displacement time history curve and characteristic point wake diagram: (a) Dimensionless amplitude 0.1; (b) Dimensionless amplitude 1.1.

### 5.3. Effects of Damping

Figure 6 shows the relationship between the flow velocity and the maximum vibration amplitude for the three sizes of AMTU that were used in the experiment. Although the maximum amplitude increased on the whole as the speed of water flow increased, this trend was not linear. Once a certain amplitude was reached, the rate of increase in amplitude decreased. As an example of this behavior,
there was virtually no change in amplitude at a vibrator diameter of 160 mm, which should have reached the “lock-in” area. Similarly, while the maximum vibration amplitude decreased after connecting the transducer unit, it remained within the acceptable range of energy conversion and eventually reached the locked state to satisfy the original intent of the design.

5.4. Potential Application
Based on the test results, the calculation can be made that for a 120 mm diameter vibrator connected to a 300 mm diameter AMTU at a low flow velocity of 0.5 m s\(^{-1}\), the vibrator can drive the energy unit to generate a vertical deformation of 70 mm. Two charge and discharge cycles can occur a power of 10 mJ can be generated. Furthermore, by arranging the transducer arrays (with 8D×5D) similar to VIVACE, energy density can be calculated as 41 W m\(^{-3}\), which indicates a strong power generation effect.

6. Conclusion
This paper proposed a novel converter with the ability to harness tidal current energy based on the VIV theory and artificial muscles. The main findings of this work are summarized as follows:

1) The introduction of the nonlinear damping of artificial muscles had an effect on both the amplitude response and the frequency response of VIV. The period of the vibration displacement curve changed with changes in the characteristics of nonlinear damping. As the damping increased, the rate of change in the vibration frequency decreased, but the increase in damping generally did not cause changes in the nature of the system.

2) According to the numerical simulation results, when the vibration system entered the lock-in area, neither amplitude nor frequency changed markedly, and the vibration displacement curve resembled a regular sine-type curve.

3) The comprehensive results of numerical simulation and prototype experiments showed that the vibration effect was best when the reduced velocity was in the range of 5 to 8. However, the self-excited vibration frequency of the system remained between 0.9 Hz and 1.2 Hz. The practical application conditions of the prototype were satisfied when the water flow velocity was in the range of 0.5 m s\(^{-1}\) to 0.75 m s\(^{-1}\).

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