# Study on an Artificial Muscle VIV Tidal Current Energy Converter with Damping

Peng Yuan [1], Shujie wang [1], Yunwen Cai [1] and Junzhe Tan[1]

[1] College of Engineering
Ocean University of China
Songling Road, No.238, Qingdao (China), 266100
phone:+86 180 53220521, e-mail: yuanpeng50@hotmail.com, wangshujie@ouc.edu.cn, 752626449@qq.com, tanjunzhe_cn@163.com

**Abstract.** A new concept of tidal current energy converter device which can directly convert energy of vortex induced vibration motion into electricity by using a kind of artificial muscle-dielectric elastomers was proposed. In order to get further understand of the dynamic performance of damped vortex induced vibration of the device, model test study was conducted. Considering mechanical characteristics, a model test rig was designed, and a series of vortex induced vibration model tests was made with cylinder oscillators of various diameters and linear and nonlinear damping were mounted on in various velocities of flow in a flume. Relevant results of the tests were analyzed. Moreover, time-domain and frequency-domain analysis were conducted, and further dynamic response behavior of the device was got. The model tests verified the feasibility of the new concept converter system and the tests results would provide valuable references for future application..

## Key words

vortex induced vibration, artificial muscle, dielectric elastomer, tidal current energy converter, ocean energy

## 1. Introduction

Tidal current energy technology has been paid more and more attention as it is considered as kind of promising ocean renewable energy for its advantages of predictable, free and sustainable. China has abundant tidal current energy resources total of which are around 13948.5MW by estimation. [1] In general, China's tidal current energy resources have features of relatively low flow rates and shallow depth albeit large in total amount. Especially in the coastal areas of northern China, there are quite a few tidal current velocities at around 1.0m/s, which is available but hard to be economically exploited.

The concept of a device based on the principle of Vortex Induce Vibration (VIV) to harness tidal current energy proposed by Michael Bernitsas[2]is considered to be an efficient way to capture power in low velocity stream. In this concept, the kinetic energy of sea water was converted into kinetic energy of the vortex induced vibrating oscillator. Here we try to enhance the efficiency of converting kinetic energy of oscillator into electricity, using a sort of electroactive polymer, commonly known as "artificial muscles" to directly convert vibration motion of the oscillator into electricity. Shown as Figure 1.

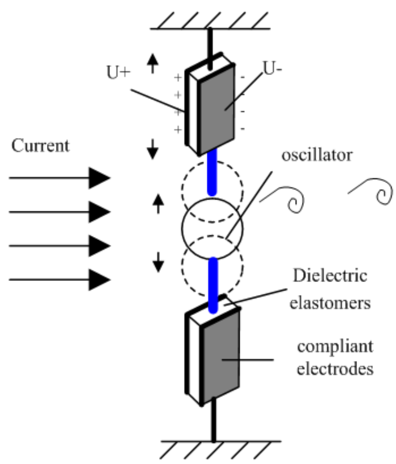



Figure.1 Schematic diagram of the device

## 2. Mathematic Model of VIV

The VIV model for study is the elastically-mounted, rigid circular cylinder in cross-flow that is restricted to motion only in the transverse direction as shown in figure 2, with the structure of the system is characterized by mass, m, and elasticity, k. the fluid characterized with the free-stream fluid velocity U, and fluid properties of density ρ and dynamic viscosity μ. The system characteristic length scale is the cylinder diameter D. The system is a classical forced mass-damper-spring system with the fluid supplying the force term. The motion law of the wake oscillator is described with the improved Van De Pol equation here.

The governing equation of motion along the cross flow direction is given by

$$m\ddot{Y}+c\dot{Y}+kY=F_L(Y) \quad (1)$$

Where $Y,\dot{Y},\ddot{Y}$ are the displacement, velocity and acceleration along the cross-flow direction. The fluid forcing term is labeled $F_L(Y)$ since only the lift component of the fluid force contributes to the motion.

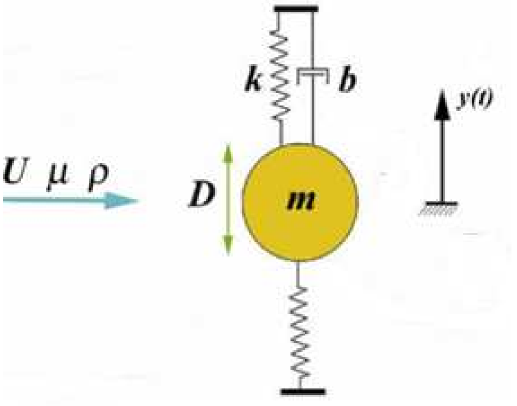



Figure.2 Diagram of the VIV system

The damping c consists of fluid damping cf and structural damping cn, where $c_f=\gamma\omega_s\rho_r D^2$. γ is defined as viscous force coefficient, closely related with the fluid damping coefficient $C_d$. k is the cylinder stiffness and $\omega_s$ is the vortex shedding frequency:

$$\omega_s=\frac{1}{f_s}=2\pi\frac{\mu S_t}{D_0} \quad (2)$$

For the one degree of freedom rigid cylinder, the natural frequency $\omega_n=(k/m)^{\frac{1}{2}}$, damping ratio is given by $\xi=c_n/(2m\omega_n)$, according to equation (1):

$$\ddot{Y}+\left[2\xi\omega_n+\frac{\gamma}{\mu}\omega_s\right]\dot{Y}+\omega_n^2 Y=\frac{F_Y}{m} \quad (3)$$

To calculating the interaction between vibrator and wake, the improved Van De Pol equation for wake oscillator model is commonly used at present:

$$\ddot{Y}+\varepsilon\omega_S\left(\eta^2-1\right)\dot{\eta}+\omega_S^2\eta=\frac{A}{D_0}\ddot{Y} \quad (4)$$

Where A is defined as fluid-structure interaction dynamic coefficients; $\varepsilon$ is a parameter in the nonlinear term; K is given by $K=\eta_0/2=C_l/C_{l0}$, representing the instantaneous vortex-induced vibration of cylinder lift coefficient $C_l$ with the corresponding static vortex-induced lift coefficient $C_{l0}$ while vortex shedding.

$$\ddot{Y}+\left(2\xi\delta+\frac{\gamma}{\mu}\right)\dot{Y}+\delta^2 Y=M\eta \quad (5)$$

$$\ddot{\eta}+\varepsilon\left(\eta^2-1\right)\dot{\eta}+\eta=A\ddot{Y} \quad (6)$$

The frequency ratio δ is:

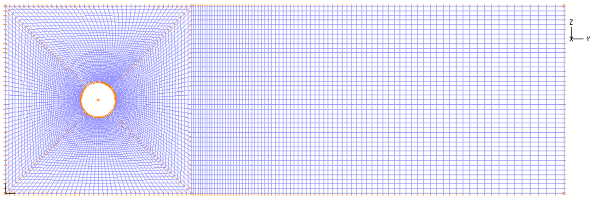
$$\delta=\frac{\omega_n}{\omega_s}=\frac{\omega_n}{2\pi S_t(\mu/D)}=\frac{1}{S_t U_r} \quad (7)$$

and the non-dimensional coupling parameters M is:

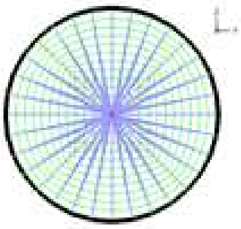
$$M=\frac{C_{l0}}{2}\frac{1}{8\pi^2 S_t^2\mu} \quad (8)$$

## 3. Numerical Simulation

To verify the mathematical model got in the previous section, numerical simulation was done using the finite element method of the two-dimensional cylindrical damping system. Flow model and oscillator model are established respectively in the finite element analysis software ADINA. Spring constrains were set on the center of the cylinder, mesh around cylinder were refined (figure 3).

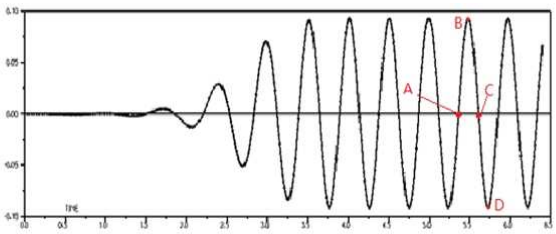


(a)Fluid domain

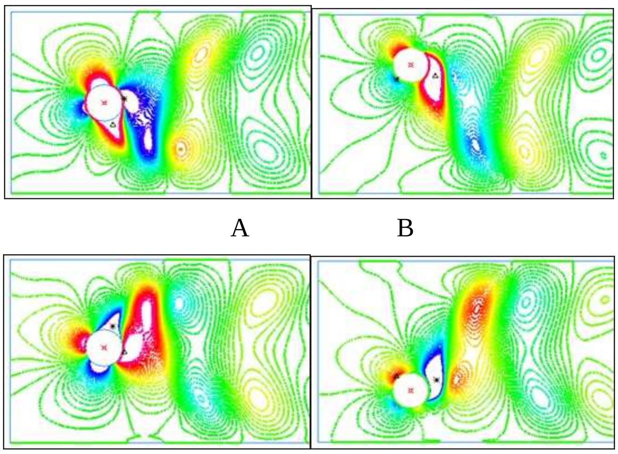


(b) Structure domain

Figure.3 Meshing fluid domain and structure domain




(a)




(b)

Figure.4 Oscillator displacement curve and wake graph, A/D=1.1

We performed the discrete equations based on the finite volume method technology FCBI-C (flow condition based interpolation), calculation by FSI (fluid structure interaction), the desired result such as vortex's generating and shedding, the steady-state resonance amplitude and frequency were got. Figure 4 showed the simulation result of the oscillator displacement time-domain curve under the condition of D=85mm, k=350N/m, v=0.7m/s. Figure4 (b) shows the instantaneous velocity of streamline chart corresponding with figure4 (a). The maximum amplitude can reach to 9.5cm and only three seconds after, the vibration will be steady.

## 4. Experiments

The experiment rig of the VIV device is shown in figure 5.

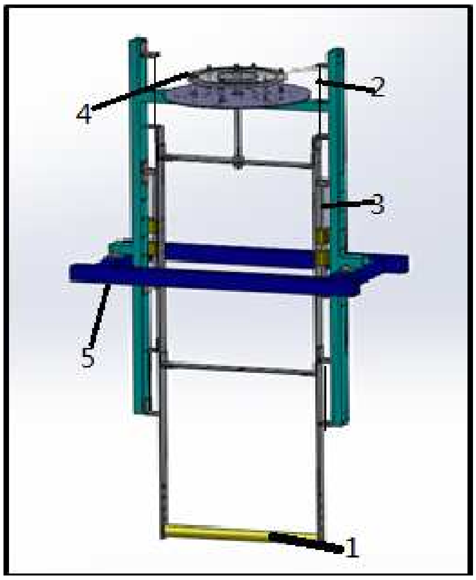



Figure.5 Diagram of the experiment rig: 1-oscillator, 2-spring, 3-rail, 4- transducer unit, 5-fixed frame

Five different sized nylon oscillators[4] were used in the experiments (Figure 6). The springs selected and used in the experiment are with 5 different elastic stiffness values. Transducer units with 4 sizes (160mm, 200mm, 240mm, and 300mm) were mounted on the frame of the rig. The transducer unit of tidal current energy conversion device is made of DE VHB4910 which is smeared evenly with electrode turbid liquid on surface. And the electrode turbid liquid is made of silicone oil, n-heptane and graphite powder mixed in certain percentage.

Consider a transducer made of a membrane of a dielectric elastomer sandwiched between two compliant electrodes. When the electrodes are subject to a voltage, the positive and negative charges spread on the two sides of the membrane, causing thickness reduction and area expansion of the membrane. Capacitance of the membrane is proportional to the area and inversely proportional to its thickness. When the electrodes are subject to a force, the decrease of its thickness causes the capacitance change. The deformation of dielectric elastomers can be induced by applying either a voltage or a force.

Figure.6 Different sizes of cylinders and its connection

This model test was conducted in Marine Dynamics Laboratory, Ocean University of China, Qingdao, as shown in figure 7.

In order to obtain the natural frequency of vibration system in water, initially excite the vibration system when water is still[5], with an initial displacement is approximately twice of the oscillator's diameter. When the number of times of vibrations is 10, the total duration of the 10 times of vibrations recorded by stopwatch is T, so the natural frequency of the system is $f_n = 10/T$.

Apply the free attenuation used in still water again in order to obtain the structural damping of prototype. Similar with frequency measurement, its procedure is to remove the exciting force after the oscillation amplitude reached A. Record the cycle index as "n" when the amplitude attenuation is half, then the damping factor $\xi$ can be calculated according to the formula below and $\xi$ =0.004775[6].

$$\frac{A_i}{A_{i+n}} = e^{2\pi\xi/\left(1-\xi^2\right)^{1/2}} \tag{9}$$

Figure.7 Experiment rig in the flume

Then experiments conducted in running water in conditions with different variables include flow rate, the diameter of oscillator, spring stiffness and the size of transducer unit. The feasibility of tidal current energy conversion device capacitation principle should be verified at the beginning of the experiment without the transducer unit. Firstly, install the oscillator with the minimum size of diameter and change successively the springs with stiffness from 200N/m to 600N/m. Starting from zero, the flow rate increases by 0.01m/s every time with the help of current meter. Until the oscillator starts to vibrate, take 0.05m/s as the increment till the maximum flow rate reaches 0.75m/s. Record the amplitude and frequency response data of VIV (vortex induced vibration). The measurement of frequency is similar with that of hydrostatic attenuation, except that the whole process is self-excited vibration without the initial excitation[7].

After the installation of transducer unit, the measurement procedures are as before, but it should be noted that, the experimental results of various variables and values' working conditions have been recorded in the former experiment of capacitation principle. Since the transducer unit added in this section will increase the whole damping and decrease the whole amplitude, here only make a variable flow rate measurement of the maximum amplitude working condition obtained from the former record.

Results of the experiment is shown in TABLE I and figure 8, figure 9.

TABLE I

The nature frequency of vibration system with different sizes of nonlinear damping

| $f_n$(Hz) | Cylinder diameter *D*（mm） | | | | |
|---|---|---|---|---|---|
| | 70 | 85 | 100 | 120 | 140 |
| *d*=160mm | 1.169 | 1.141 | 1.119 | 1.101 | 1.083 |
| *d*=200mm | 1.142 | 1.126 | 1.101 | 1.078 | 1.057 |
| *d*=240mm | 1.121 | 1.111 | 1.087 | 1.062 | 1.041 |
| *d*=300mm | 1.109 | 1.098 | 1.065 | 1.044 | 1.026 |

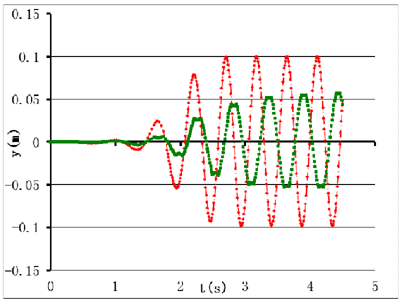



Figure.8 The curve of displacement of the oscillator over time

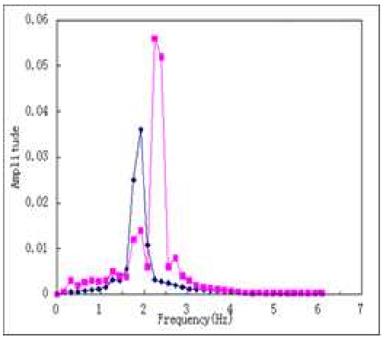
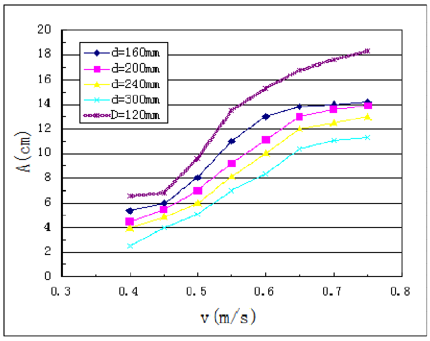



Figure.9 Frequency curves

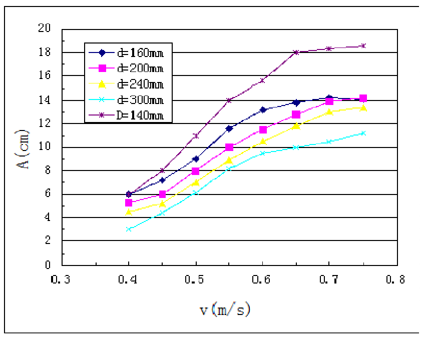
Table II shows the nature frequency of vibration system with different sizes of nonlinear damping. And as shown in figure 8, the green curve represents the displacement time-domain curve on the condition that D (the diameter of oscillator) is 85mm, spring stiffness is 350N/m, flow rate is 0.7m/s and d (the diameter of unit) is 300mm. As a control, the red curve represents the displacement time-domain curve of linear damping on the same condition. As can be seen from the figure, after the increase of the damping, the system vibration displacement obviously decreases, but the time of starting oscillation and reaching steady state extend, which is caused by the transducer unit's energy dissipation to vibration system. Moreover, due to the nonlinearity of transducer unit damping, the displacement time-domain curve appears a periodic fluctuation.

Frequency results can be got by the Fourier Transform of vibration displacement, as shown in figure 9, which is corresponding to figure 8. As can be seen from figure 9, the amplitude and range of frequency distinctly decrease after the adding of transducer unit, but the optimum frequency value is very close.

Figure 10 shows the relationship between velocity and amplitude of different diameters of transducer units. (a) With the cylinder diameter D=120mm, and (b) with D=140mm. As a control, the purple curve represents the curve of linear damping on the same condition.




(a) D=120mm




(b) D=140mm

Figure.10 The relationship between velocity and maximum amplitude of different diameters of transducer units

TABLE II

The amplitude attenuation ratio of different sizes

of nonlinear damping

| | *d*=160mm | *d*=200mm | *d*=240mm | *d*=300mm |
|---|---|---|---|---|
| *D*=120mm | 17.61% | 25.84% | 33.25% | 43.04% |
| *D*=140mm | 17.46% | 23.16% | 32.99% | 43.93% |

According to the experimental results, here list the amplitude attenuation ratio of four sizes of nonlinear damping shown in table II. Clearly, the transducer unit with small diameter can get the smaller loss of amplitude response.

## 5. Conclusion

A new concept of tidal current energy converter device which can directly convert energy of vortex induced vibration motion into electricity by using a kind of artificial muscle-dielectric elastomers was proposed. By numerical simulation and flume experiments, a prototype of the device was studied. Some conclusions were got as follows:

(a)Under the same value of spring stiffness and flow velocity, the smaller the diameter of transducer unit, the greater the deformation displacement.

(b)Under the same value of spring stiffness and flow velocity, the greater diameter of oscillator, the greater amplitude can be got.

(c)Under the same value of spring stiffness and cylinder diameter, the greater flow velocity, the greater amplitude response.

(d)Nonlinear damping made the maximum amplitude decrease and the displacement time-domain curve appears a periodic fluctuation. Generally speaking, though the adding of nonlinear damping has an impact both on amplitude and frequency response, it doesn’t cause a change in nature.

## Acknowledgement

The project supported by National Natural Science Foundation of China (grant no. 51176175). The authors are grateful for the financial support.

## References

[1] Shujie Wang, Peng Yuan, Dong Li, Yuhe Jiao, An overview of ocean renewable energy in China. Renewable and Sustainable Energy Reviews, 2011.Vol 15.1, pp.91-111.

[2] M.M. Bernitsas, K. Raghavan, Y. Ben-Simon, E. M. H. Garcia, VIVACE (Vortex Induced Vibration Aquatic Clean Energy): A New Concept in Generation of Clean and Renewable Energy from Fluid Flow, Journal of Offshore Mechanics and Arctic Engineering, ASME Transactions, Nov. 2008, Vol. 130, No. 4, pp. 041101-15.

[3] Joseph Thomas Klamo. Effects of damping and Reynolds number on vortex-induced vibrations.2007.pp.1-2.

[4] Mao Liangjie, Liu Qingyou, ZhouShouwei. Experimental study of the vortex-induced vibration of drilling risers under the shear flow with the same shear parameter at the different Reynolds numbers. Published online 2014 Aug 13. doi: 10.1371/journal.pone.0104806

[5] Raghavan K, Bernitsas MM Experimental investigation of Reynoldsnumber effect on vortex-induced vibration of rigid circular cylinder on elasticsupports. Ocean Eng 38: 719-731.

[6] Trim AD, Braaten H, Lie H, Tognarelli MA.Experimental investigationof vortex-induced vibration of long marine risers. .Fluids Struct.2005, 21: pp.335-361.

[7] Blevins RD, Coughran CS.Experimental investigation ofvortex-induced vibration in one and two dimensions with variablemass, damping, and Reynolds number. Fluids Eng,.2009, 131(06):pp.128-139.