Research Status and Key Technologies of Flow-Induced Vibration Power Generation Devices

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Abstract

As the global economy continues to thrive, the demand for oil and gas energy resources is steadily increasing. However, the finite reserves of fossil fuels are depleting rapidly, making the development of renewable energy sources an urgent necessity. Tidal energy, as a clean and renewable energy source, is gradually playing an increasingly significant role in the global energy landscape. Currently, there are two primary methods for tidal energy generation. One approach involves the use of underwater turbines driven by high-speed water currents to turn turbines and generate electricity. While this method boasts high energy conversion efficiency, it requires substantial flow velocities, limiting its applicability. The other method capitalizes on the phenomenon of flow-induced vibrations to convert the kinetic energy of water flow into electrical energy. This approach is characterized by its ability to efficiently generate power at low flow speeds, making it of paramount importance for enhancing the utilization of renewable energy sources in our country. By analyzing the principles and key technologies of flow-induced vibration power generation and considering the current state of research in this field, this study aims to provide insights into the future development and research directions of flow-induced vibration power generation. The ultimate goal is to offer new perspectives for the promotion and utilization of renewable energy sources.

Keywords

Ttidal Energy; Flow-Induced Vibration; Conversion Efficiency; Energy Utilization.

1. Introduction

In today's world, the importance of renewable energy is becoming increasingly prominent. Faced with climate change and finite fossil fuel resources, scientists have been searching for innovative energy solutions to meet growing energy demands and reduce adverse environmental impacts. Hydropower, as a clean and renewable energy source, is playing an increasingly important role in the global energy structure. Ocean currents possess a wide distribution of energy and a high energy density. Currently, there are two main methods for generating electricity using ocean currents: one is to use underwater turbines (water turbines) to extract hydrodynamic energy. Its power generation principle is to use high-speed water flow to drive an impeller, which in turn drives a generator to generate electricity. While it boasts high energy conversion efficiency and high energy density, this also places demands on the starting flow rate; effective energy conversion is difficult to achieve at low flow rates. Submersible turbines can only work effectively when the water flow velocity is at least 1.5 m/s. Although my country has abundant ocean current energy resources, the flow velocity is low[1], with an average flow velocity of 0.5~1.5 m/s[2]. This means that water turbines cannot be used in most sea areas. Secondly, it utilizes the alternating lift generated by flow-induced vibration to convert the kinetic energy of the water flow into the mechanical energy of the device, and then into electrical energy. Unlike a water turbine, this device can start generating electricity at a relatively low flow

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velocity (0.25 m/s). Currently, the research on flow-induced vibration power generation has not yet formed a complete theoretical system. Therefore, this paper comprehensively reviews the current research status of flow-induced vibration power generation, systematically summarizes the basic principles, advantages, current technological progress, and applications of existing flow-induced vibration power generation equipment, and proposes the main contents of future research on flow-induced vibration energy harvesting. The purpose of this paper is to provide a good reference for subsequent research on the development of flow-induced vibration power generation equipment and energy extraction.

2. Theoretical Background

2.1 Flow-induced Vibration

Flow-induced motion refers to the phenomenon where fluids exert alternating fluid forces on the surface of a solid as they flow through it, causing the solid to reciprocate. The reciprocating motion of the solid changes the fluid flow state, which in turn changes the fluid forces acting on the solid surface. This phenomenon of fluid-solid interaction is called flow-induced motion[3]. As shown in Fig. 1, FIVs are mainly divided into two types: (1) resonance, such as buffeting and vortex-induced vibrations; and (2) unstable vibrations, such as galloping and flutter. In the resonance type of flow-induced vibrations, the object will start to oscillate once the frequency of the oscillating force is close to the natural frequency of the system. If the vibration is caused by the force generated by the alternating shedding vortices, it is called vortex-induced vibration. If the airfoil oscillates due to the oscillation of the incoming flow, it is called buffeting. In the unstable vibration type, galloping and flutter are both started at a certain critical flow velocity. Unlike the resonance type, the oscillation of the object will increase with the increase of the flow velocity.

Among flow-induced vibrations, vortex-induced vibration and galloping are the most common. Vortex-induced vibration refers to the phenomenon where, when a free flow passes over a blunt-nosed body, boundary layer flow separation occurs at a certain angle. This results in alternating detachment vortices on the upper and lower sides of the blunt-nosed body, which further causes pressure changes on the surface of the blunt-nosed body. This creates periodic pulsating forces on the surface of the blunt-nosed body. When the blunt-nosed body is elastically supported or can undergo elastic deformation, the pulsating forces act as external excitation, causing the blunt-nosed body to vibrate periodically. This vibration caused by alternating detachment vortices is called vortex-induced vibration. When the vortex shedding frequency is very close to the natural frequency of the blunt-nosed body, the blunt-nosed body will resonate and exhibit a "synchronization" phenomenon. Galloping refers to the hydrodynamic negative damping that occurs when a blunt-nosed body vibrates at a certain angle of attack relative to the free flow under certain conditions. This causes the blunt-nosed body's vibration to diverge, leading to system instability. Galloping is a motion perpendicular to the water flow, characterized by low frequency, large amplitude, and both self-excitation and divergent properties. For the same structure, the flow velocity at which galloping begins is greater than that of vortex-induced vibration; therefore, vortex-induced vibration sometimes precedes galloping. Unlike vortex-induced vibration, galloping vibration has no synchronization region and cannot be self-limiting. Unless constrained by a return spring or structural configuration, the amplitude will increase with increasing flow velocity until structural failure occurs. Both vortex-induced vibration and galloping vibration can produce large amplitudes, and when the amplitude becomes large enough, it can cause damage to the structure. Therefore, it was previously considered a harmful phenomenon, and scholars and engineers have focused their research on how to suppress flow-induced vibrations to ensure the stability of structures[4-6]. Until recently, with the rapid development of electronic technology and marine new energy fields, it has been discovered that the energy contained in flow-induced vibrations can be effectively utilized through certain devices, showing great promise. Professor Michael Bernitsas of the University of Michigan proposed a new concept for extracting renewable energy from flow-induced vibrations and designed VIVACE (Vortex-induced vibrations for aquatic clean energy).

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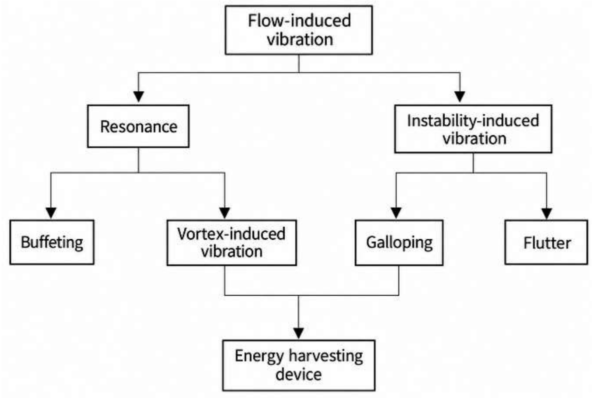

Fig. 1 Classification of flow-induced oscillations Diagram

2.2 Mathematical Model

As shown in Fig. 2, Bernitsas simplifies the flow-induced vibration of an elastically supported cylinder as a mass-spring-damped system. The equation of motion for the cylinder was then derived,

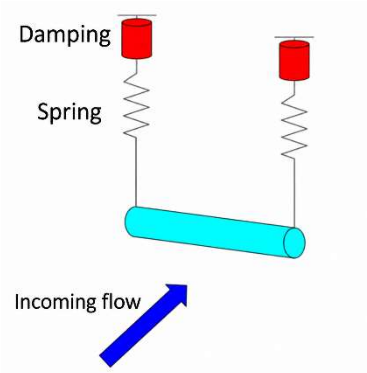

Fig. 2 VIVACE Module Simple Schematic Diagram

and based on this, the formulas for calculating the power extracted from the water flow by the VIVACE device and its energy conversion efficiency were derived. The Reynolds number and reduced velocity are defined as follows:

$$Re = \frac{UD}{v} \tag{1}$$

$$U^* = \frac{U}{f_{n,\,water}D} \tag{2}$$

In the formula, U , D , v and represent the incoming flow velocity, column diameter, and kinematic viscosity, respectively. $f_{n,water}$The natural frequency in still water is defined as:

$$f_{n,\,water} = \frac{1}{2\pi}\sqrt{\frac{K}{m_{osc} + m_a}} \tag{3}$$

In the formula, K is the spring stiffness, m_{osc} is the oscillating mass, and m_a is the additional mass.

The linear equation of the cylinder is:

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$$m_{osc}\ddot{y} + c_{total}y + k\dot{y} = F_{fluid} \tag{4}$$

Power in the fluid (available power):

$$P_{fluid} = \frac{1}{2}\rho U^3 DL \tag{5}$$

During one oscillation cycle, the work done by the fluid force on the cylinder is:

$$W_{VIVACE} = \int_0^{Tcyl} F_{fluid}\dot{y}dt \tag{6}$$

Therefore, the mechanical power of VIVACE is:

$$P_{VIVIACE} = \frac{W_{VIVACE}}{T_{cyl}} \tag{7}$$

Substituting equation (4) into equation (5) yields

$$P_{VIVIACE} = \frac{1}{T_{cyl}}\int_0^{Tcyl} (m_{osc}\ddot{y} + c_{total}y + k\dot{y})\ \dot{y}dt \tag{8}$$

The overall damping coefficient of a cylinder is the sum of structural damping and energy-harvesting damping:

$$C_{total} = C_{structure} + C_{harness} \tag{9}$$

In VIVACE, the usable power is the power extracted by the generator, which is equal to the power extracted by VIVACE from the fluid minus the power consumed due to structure, transmission, and internal generator losses.

Energy harvesting efficiency is defined as the ratio of power output to available power:

$$\eta_{VIVIACE} = \frac{P_{VIVACE}}{P_{fluid}} = \frac{P_{VIVACE}}{\frac{1}{2}\rho U^3 DL} \tag{10}$$

3. Current Status of Research on Flow-Induced Vibration Power Generation Devices

Currently, there are two main methods of flow-induced vibration power generation: electromagnetic and piezoelectric[7].Piezoelectricity is a special charge separation phenomenon that relies on the piezoelectric effect[8]. When certain crystal materials are subjected to mechanical stress or pressure, charge separation occurs, generating a potential difference (voltage). This potential difference can be captured and utilized through a connected circuit to achieve the purpose of generating electricity. At present, research on piezoelectric flow-induced vibration power generation devices is not widespread.

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This is mainly because the energy harvesting efficiency of such devices is relatively low, the energy harvesting flow rate range is also relatively limited, and the energy harvesting stability is not high. They are more often used in small-power micro devices, which limits their practical application value in the engineering field[9]. Electromagnetic power generation relies on electromagnetic induction (when a conductor in a closed circuit moves through a magnetic field, cutting magnetic field lines, a current is generated in the conductor) to generate electricity. Compared to traditional methods, electromagnetic power generation devices have higher energy density and stronger energy harvesting capabilities, making them more suitable for large-scale energy conversion.

The VIVACE device, developed by Professor Bernitsas and his research team at the University of Michigan, is a type of electromagnetic power generation and represents a significant breakthrough in the conversion of energy from flow-induced vibrations. A schematic diagram of the device is shown in Fig. 3. It mainly consists of three parts: (1) a vibrating cylinder, which converts the ocean current energy generated by the flow-induced vibration into mechanical energy; (2) a transmission structure, including springs, bearings, gears and racks, etc., which ensure the continuous vibration and motion transmission of the oscillator in the direction perpendicular to the water flow; and (3) a generator, which converts the mechanical energy transmitted by the transmission structure into electrical energy. When water flows over a cylindrical oscillator, it generates flow-induced vibrations under certain conditions. The kinetic energy of the oscillator is then transferred to a rotating generator (which consists of a stator and a mover) via a transmission structure. The kinetic energy of the oscillator is converted into the mechanical energy of the mover, which in turn cuts magnetic field lines to generate electrical energy.

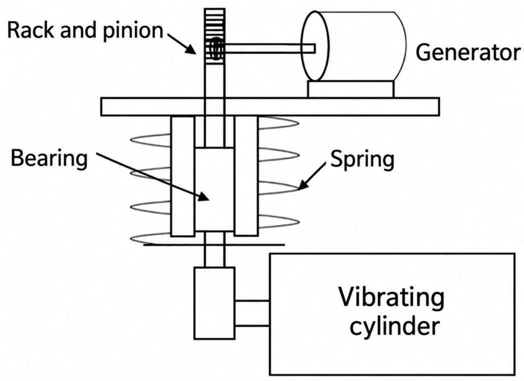

Fig. 3 Schematic Diagram of VIVACE

Currently, the relevant literature on generating electricity using the principle of flow-induced vibration mainly comes from Professor Michael Bernitsas and his team at the University of Michigan. The following is a summary of their team and the current research status in China.

In 2008, Professor Bernitsas's research team[10] designed a laboratory prototype and conducted several experiments of different scales at the University of Michigan laboratory in the United States. The maximum actual power reached 165 kW. It meets all the requirements set by the California Energy Commission and the U.S. Department of Energy: (1) It will not have a significant impact on navigation, marine life and coastal real estate resources; (2) It has a simple structure, with all mechanical and electrical components underwater; (3) It is robust and durable, ensuring a lifespan of at least 20 years; (4) It has high energy density; (5) It is highly compatible and can be used all year round; (6) It is not limited by flow rate and can efficiently obtain energy even at lower flow rates. At higher flow rates, it can extract more energy. Meanwhile, K. Raghavan et al.[11] defined a new concept, gap ratio (G/D, which is the ratio of the distance from the cylinder to the bottom boundary to the diameter of the cylinder). Experiments showed that for G/D>3, the influence of the bottom boundary on VIV can be ignored. This means that under certain conditions, the size and complexity

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of the bottom structure can be reduced while maintaining high-efficiency energy conversion, which provides important help for the design and performance of VIVACE converters.

The amplitude of a column's motion is a crucial measurement that effectively describes and quantifies flow-induced vibration phenomena. System stiffness determines the column's response to vibration, while damping modulates the degree of vibration attenuation. The mass ratio describes the column's mass relative to the surrounding fluid, and surface roughness alters the fluid environment's effect on the column. All these parameters significantly influence the column's amplitude. Therefore, subsequent studies mainly focused on adjusting these important parameters. Hai Sun et al.[12] investigated the effects of mass ratio, damping, and stiffness on the energy gain efficiency of flow-induced vibration of a single cylinder at Reynolds numbers of 30,000 ≤ 120,000. The study found that (1) for a given damping, when the mass ratio increased from 1.007 to 1.685, the peak energy gain power of the upper branch of vortex-induced vibration increased by 98%, and the peak energy gain power of the galloping region increased by 69%. (2) A spring with low stiffness will increase the transition area between vortex-induced vibration and galloping, resulting in a lower energy density. By increasing the stiffness of the spring, the "synchronization" time of vortex-induced vibration can be extended to compensate for the gap generated by the transition. Bernitsas et al.[13] conducted high-damping, high-Reynolds-number tests on the VIVACE converter, which consisted of cylinders mounted on elastic springs, at the Ocean Hydrodynamics Laboratory of the University of Michigan. At a flow velocity of U = 0.840 m/s, the maximum peak efficiency was found to be η_{peak} =0.308, and the average efficiency was η =0.22. The experimental results demonstrate that even at low speeds where water turbines and turbines cannot operate effectively, VIVACE can efficiently convert kinetic energy into electrical energy. This implies that VIVACE has wider applicability and is of great significance for energy utilization. Bai Xu et al.[14] analyzed the parameters affecting the energy acquisition efficiency of vortex-induced vibration. They combined the mass-spring-damped oscillator model, integrated the power over time, and established the energy acquisition efficiency formula for column vortex-induced vibration. Through numerical simulation and combined with the efficiency formula, they found that the energy acquisition efficiency was the highest under the conditions of reduced velocity = 12.5, damping ratio coefficient = 0.081, and mass ratio = 1.48.

In addition, as a mechanical device, VIVACE experiences energy loss during energy conversion. The first-generation VIVACE used a crank mechanism as a transmission device to connect the oscillator and the generator. Although the crank mechanism is simple to manufacture and easy to implement, it occupies a large amount of space. Zhang Chenglong[15] compared several different mechanisms on VIVACE that could convert linear motion into rotational motion, analyzed their advantages and disadvantages, and concluded that the most suitable mechanism for the power generation device was the one that could be used. At the same time, he proposed a new series device to enable two power generation devices to share one generator, thereby reducing costs. Nonlinear oscillators have a wider range of applications, adaptability, and control performance. Therefore, Hai Sun and Chunhui Ma[16] extended the concept of nonlinear stiffness to displacement adaptation using piecewise linear and cubic stiffness functions. In the experiment, the minimum flow velocity for energy harvesting in the nonlinear case decreased to 0.275 m/s, lower than in the linear case. Furthermore, at the start of galloping, the efficiency of this nonlinear oscillator was 1.76 times that of the linear spring oscillator. As the flow velocity further increased, the difference narrowed to 1.15 times. Under low damping conditions, the instantaneous natural frequency of the cubic-end spring oscillator changes with the vibration amplitude, expanding the "synchronization" range, reducing the gap between vortex-induced vibration and galloping vibration, and exhibiting stable oscillation, resulting in a 78.6% increase in VIVACE's energy harvesting power. The results show that one local optimum of energy harvesting occurs in the VIV at the end of the upper branch, while another local optimum occurs at the maximum allowable speed of galloping due to facility limitations. Based on extensive research, the upper branch is the primary energy harvesting location for VIVACE, and a nonlinear cubic stiffness oscillator will extend the upper branch of the VIV, thereby expanding the energy harvesting range utilized by the oscillator.

Zhang Jun and Yan Xiang[17,18] conducted flow-induced vibration experiments on rigid oscillators with different cross-sectional shapes under elastic support. The cross-sectional shapes of the tested oscillators were circular, equilateral triangular, square, and regular hexagonal. The purpose of the experimental study was to explore and compare the flow-induced vibration characteristics of oscillators with different cross-sectional shapes, so as to determine the appropriate cross-sectional shapes of oscillators for the utilization of flow-induced vibration energy and their corresponding applicable conditions. Based on the amplitude, frequency, and stability response characteristics of oscillators with four different cross-sectional shapes, it is concluded that circular and equilateral triangular cross-sectional shapes are more suitable for energy utilization of flow-induced vibrations. A circular shape is only suitable for environmental conditions with low flow velocity and small flow velocity variations, while an equilateral triangle is suitable for environmental conditions with high flow velocity and large flow velocity variations. Furthermore, increasing stiffness is beneficial for energy extraction by a circular cross-section oscillator, while decreasing stiffness is beneficial for energy extraction by a triangular cross-section oscillator. However, the effects of different cross-sectional shapes and the number of oscillators on flow-induced vibration power generation devices still require further in-depth research.

For traditional single-cylinder vortex-induced vibration, its flow-induced vibration has the characteristic of "self-limitation", that is, the oscillator only maintains strong flow-induced vibration within a certain flow velocity range[19-26]. This characteristic reduces the energy conversion performance of the VIVACE device to some extent, resulting in low energy conversion efficiency and a limited applicable flow velocity range. To utilize the kinetic energy of low-speed ocean currents or rivers on a large scale, the energy converter should consist of a large number of cylinders. By cleverly configuring densely arranged energy converters, the interstitial flow and wake interference effects between adjacent cylinders can be utilized to enhance fluid-structure interaction and achieve coordinated operation between cylindrical oscillators. Among them, the interference effect between two cylindrical systems is the most studied due to its simplicity. Due to the mutual interference between cylinders, the flow-induced vibration response and energy utilization of a multi-cylinder system differ from those of a single-cylinder system. The interactions between the cylinders are highly complex but induce nonlinear behavior, significantly enhancing the utilized power. This complexity stems from the interactions between the boundary layer, shear layer, eddies, and cylinders.

Ribeiro et al. [27]used the SST turbulence model in CFX to study the effects of spacing and reduced velocity on the wake interference of two-dimensional tandem cylinders. Zhao[28] studied the flow-induced vibration problem of tandem and parallel double cylinders in a transverse single-degree-of-freedom vibration system under the conditions of Reynolds number Re=150 and mass ratio $m^*=2$. Ji Chunning [29]conducted a numerical simulation of a series of two cylinders at Re=100. The study found that there is mutual interference between the upstream and downstream cylinders. Regardless of whether the upstream cylinder is in a static or vibrating state, the amplitude response of the downstream cylinder is greater than that of a single cylinder. The interference effect depends largely on the cylinder arrangement, flow details, and Reynolds number. For two cylinders, there are three possible states: (1) the two cylinders are close to each other and influence each other; (2) one cylinder is located at the wake position of the other cylinder, causing wake interference; (3) the two cylinders are far enough apart to be in a relatively opposing state. However, in a multi-cylinder system arrangement, the downstream cylinder is not only affected by the impact of shedding vortices, but also by the high-level turbulence generated by the upstream cylinder. Therefore, the flow-induced motion of three or more cylinders is expected to be more complex. Kim [30,31]first conducted flow-induced vibration experiments with different numbers of oscillators, and their research showed that even though the horizontal distance between two tandem cylinders exceeded 2D, all cylinders still experienced very high-amplitude galloping. Furthermore, when the flow rate is $Re=5.64*10^4$, the power conversion efficiency increases by 2.5-7.5 times for two cylinders and by 3.4-5.26 times for

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three cylinders at different flow velocities. This is a significant breakthrough, as the power conversion efficiency increases with the number of cylindrical oscillators. When the flow rate is in the range of 0.83 m/s to 1.08 m/s, the power conversion efficiency of four cylinders exceeds 70% regardless of the center distance between the cylinders. At a flow velocity of 1.08 m/s, the maximum power conversion efficiency of the four cylinders can reach 88.6%, equivalent to the peak efficiency of a wind turbine. When the flow velocity reaches 1.45 m/s, the spatial power density of the system can reach 847.7 W/m³, achieving both high power volume density and high power conversion efficiency. Luo Zhumei[32] analyzed the flow-induced vibration characteristics and energy acquisition of four cylinders and found that the acquired hydrodynamic energy and energy density first increased with the increase of the combination spacing ratio, and then the energy acquisition increased slowly, while the energy density continued to decrease. This emphasized the importance of adjusting the spacing ratio of the cylinders to optimize energy acquisition in a multi-cylinder system.

In summary, the energy harvesting effect of electromagnetic flow-induced vibration power generation devices is significantly better than that of piezoelectric power generation devices. Specifically, electromagnetic devices offer greater energy harvesting capacity, higher energy harvesting efficiency, and a wider "synchronous" vibration range, making them highly suitable for practical engineering applications. Currently, piezoelectric power generation technology is mainly used in small-power micro-devices, so research on improving the energy conversion efficiency and lifespan of piezoelectric materials will be crucial. To improve the VIVACE system, researchers adjusted key parameters such as mass ratio, damping, stiffness, and surface roughness, thereby increasing the system's energy conversion efficiency. Subsequent research revealed that densely packed oscillators significantly enhance the synergistic effect of flow-induced vibration, boosting both energy density and energy conversion efficiency, particularly in low-velocity water flows. This demonstrates the feasibility of large-scale hydrodynamic projects.

4. Key Technology Research

4.1 Virtual Damped Spring Testing System

Early in the development of VIVACE, Bernitsas discovered that parameters had a significant impact on the energy harvesting power. To maximize power output, system parameters had to be optimized, requiring multiple sets of tests under varying spring stiffness and damping values. Since the first VIVACE consisted of a cylinder supported by physically linear springs and a rotary generator, replacing physical components was extremely time-consuming. Therefore, a Vck system (virtual damped spring testing system) was developed to overcome these difficulties. In 2011, a controller was introduced to set the spring stiffness, thus realizing the simulation of a damped spring system. Lee and Bernitsas[33] used the Vck system to study the effects of spring stiffness and control damping on power output in a flow velocity range of 0.4 m/s to 1.1 m/s and a spring stiffness range of 400 N/m to 1800 N/m. The results show that the maximum amplitude observed at K=1200 N/m is 1.78D. Furthermore, because increasing the spring stiffness directly enhances the restoring force acting on the cylinder, the "synchronization" range of vortex-induced vibration shifts to a higher flow velocity range, and optimal energy gain and dissipation power curves are obtained. The maximum power increases with the value of the spring stiffness K. When K = 1800 N/m, the maximum utilized power at U = 1.11 m/s is 15.85 W. The optimal power gain and power dissipation curves were obtained. In experiments, compared to the first-generation VIVACE system without the Vck system, even with a smaller cylinder diameter, the peak power output increased by 44%. To date, two generations of Vck systems have been developed. The first-generation Vck system is shown in Fig. 4. In the figure, 1 is the controller board embedded in the computer, 2 is the interactive universal interface, 3 is the motor and embedded encoder, and 4 is the servo drive motor.

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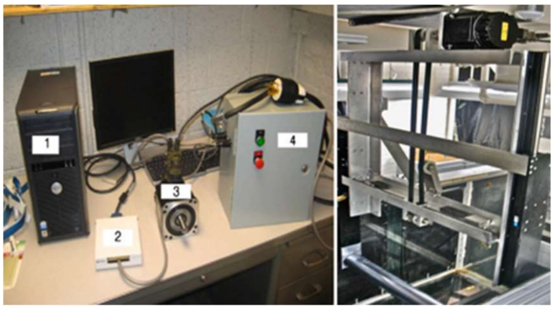

Fig. 4 Schematic Diagram of the First Generation Vck Motor Control System

Hai Sun developed the second-generation VCK system based on the first-generation VCK system[34]. Its control diagram is shown in Fig. 5. It mainly consists of a control module, an AD&DA converter, an amplifier, and a servo motor to form a feedback loop. The experiment used spring stiffnesses of 400 N/m and 600 N/m to verify the effectiveness of the virtual system. The consistency between the physical and virtual springs and dampers is excellent throughout the entire range of spring constants and test speeds. The main improvements of the new Vck system are (1) it is developed as a standalone application through an embedded controller; and (2) it uses digital signals instead of the original digital signals. The utilization of flow-induced vibration energy was tested when the damping ratio was 0.00 < < 0.24. It was found that the embedded Vck system can achieve different mass ratios, variable stiffness k, and damping c to provide optimal parameters for VIVACE.

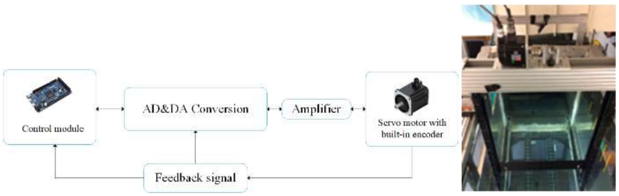

Fig.5 Schematic Diagram of the Second Generation Vck Control System

4.2 Passive Turbulence Control (PTC) Technology

The flow in a single smooth cylinder does not induce galloping, but geometric asymmetry or upstream flow asymmetry can trigger it. Therefore, to explore the conditions under which galloping occurs and to extend the energy harvesting range beyond galloping vortex-induced vibration, it is necessary to modify the flow field characteristics of the cylindrical oscillator. Control techniques for vortex shedding and flow-induced vibration in flow around a cylinder can be divided into passive turbulence control (PTC) and active turbulence control (ACTC). PTC does not require external energy input; it simply adds additional devices to the flow field to alter the shear layer separation mechanism around the oscillator, thus delaying or accelerating fluid separation. For example, changing the surface roughness of the oscillator can effectively alter its surface pressure distribution, thereby causing changes in the oscillator's lift and drag. Active control technology primarily alters the flow field through external excitation, thereby controlling fluid separation and eddy current removal to achieve the goal of controlling flow-induced vibration. PTC is widely used and easy to implement in flow-induced vibration[35].

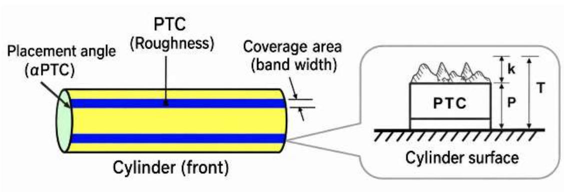

Fig. 6 Distribution Map of PTC on the Cylinder

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The passive turbulence control (PTC) device is applied to a cylindrical oscillator using two straight, rough strips of variable width and approximately equal thickness to the boundary layer. This changes the circumferential position αPTC and the surface roughness. As shown in Fig. 6, the position of the PTC is defined by the "placement angle" αPTC. A higher P value indicates a smoother surface stripe. The total thickness T of the PTC strip is defined as T = k + P, where k is the roughness height and P is the paper thickness.

Chang and Bernitsas[36] experimentally studied the effect of the passive turbulence control device PTC on the energy gain of VIVACE. It was found that, without changing other conditions, vortex-induced vibration and galloping occurred earlier when using PTC, and the "synchronization" range increased. The main reasons are attributed to (1) the change in smoothness characteristics causing the boundary layer to skip the transition from laminar to turbulent flow, and (2) fixing the split point on the surface of the cylinder and utilizing the negative damping generated by the angle of attack effect, thereby causing galloping to occur earlier. Experimental results show that the use of PTC extends the "synchronization" range of vortex-induced vibration from approximately 10 to approximately 15 or even larger. Due to the increased synchronization range, the fluid kinetic energy utilized by VIVACE increases by nearly four times. The use of a cylinder with a PTC (Power Transmitter Charge) enables a transition from vortex-induced vibration to galloping vibration, and increases the synchronization range and amplitude of flow-induced vibration. This innovation allows VIVACE to extract water kinetic energy from any fluid with a velocity greater than 0.35 m/s. Meanwhile, PTC technology allows multiple oscillators to fully exert their synergistic effect, enhancing energy density, which is of great significance for studying the flow-induced motion of multiple oscillators. Besides roughness, the height of the PTC also affects the oscillation amplitude and frequency response of the cylindrical oscillator. Its placement angle also plays a crucial role. There seems to be an optimal PTC placement angle that achieves the highest power output, but an ideal angle has not yet been found. Further experimental research will explore the PTC coverage width, whether the PTC covers single or multiple segmented regions, and the PTC arrangement method.

4.3 Adaptive Damping

The oscillation of a cylinder is determined by its damping and its stiffness, mass, or natural frequency. Under lower damping, the cylinder oscillates with a higher amplitude, leading to greater destructiveness and lower conversion efficiency. However, higher damping leads to a reduction in the amplitude and range of the flow-induced vibration response, thereby suppressing the flow-induced motion. In real-world environments, the damping coefficient is not only related to the free flow velocity but also affected by the cylinder velocity. To optimize energy conversion efficiency, we need to adjust the damping coefficient according to the cylinder's velocity. Therefore, Hai Sun and Bernitsas[37-40] proposed a hydrodynamic energy converter based on nonlinear adaptive damping, which can adjust parameters in real time according to external conditions and system state to optimize energy harvesting efficiency. The study found that: (1) in the VIV region, the damping coefficient does not affect the oscillation amplitude and frequency range, and can effectively suppress unstable oscillations at low speeds; (2) in the transition region from VIV to gallop, the damping coefficient can automatically adjust to maintain the oscillation speed and power output, avoiding the oscillation attenuation and power drop that occur in linear damped converters; (3) In the galloping region, the damping coefficient increases with the oscillation velocity, thereby improving power output and efficiency; (4) The maximum power output of the nonlinear adaptive damping converter is 51%-95% higher than that of the linear damping converter across the entire flow velocity range.

In 2020, Hai Sun further investigated the effect of adaptive damping on the flow-induced vibration of a series of two cylinders, one of the aims being to reduce the shielding effect of the upstream cylinder on the downstream cylinder. Furthermore, in the VIV region, both power and efficiency increased with the increase of the nonlinear damping coefficient. Specifically, energy gain increased by 34% in the VIV-to-galvanization transition region and by 33% in the initial stage of galloping.

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Among the single-cylinder flow-induced vibration power generation devices currently under research, the adaptive damping power generation device achieved the highest energy gain in testing. This is due to the multiple advantages of adaptive damping; it can adjust the damping level in real time according to the actual vibration conditions, ensuring that the system can achieve optimal energy conversion efficiency under different flow velocities and vibration conditions. This not only maximizes energy capture and conversion, improving device performance, but also enables the flow-induced vibration device to remain effective under a wider range of conditions. Meanwhile, adaptive damping enhances the system's stability, making it more resistant to external disturbances and changes, and contributing to long-term reliable operation. Most importantly, it also reduces unnecessary energy waste, ensures maximum energy efficiency, and lowers energy costs. These factors together make adaptive damping a key technology for flow-induced vibration power generation devices, supporting their performance and sustainability.

5. Conclusion

Currently, significant progress has been made in the research of flow-induced vibration energy utilization, with a series of flow-induced vibration energy conversion devices being proposed, and the power generation of electromagnetic power conversion devices is already quite substantial. It can be said that the overall research on the utilization of flow-induced vibration energy is progressing steadily. Researchers are maximizing the conversion efficiency and harvested power of flow-induced vibration energy harvesting devices by changing system parameters such as mass ratio, natural frequency, stiffness, damping, and by altering the structure of the oscillator to change the flow field characteristics. This article summarizes the current research status of flow-induced vibration power generation devices and the many significant contributions made by the MRELab research team to flow-induced vibration. The conclusion is as follows:

(1) Since flow-induced vibration is usually triggered by the shedding of eddy currents from the oscillator, using oscillators of different shapes is an effective way to change the vibration response without changing the energy harvesting device. As a non-self-limiting vibration, once galloping begins, the amplitude of the oscillator is much greater than VIV. Non-circular cross sections can trigger galloping better, such as square, rectangular, and triangular cross sections. However, circular cross section oscillators are currently the most commonly used. Therefore, in galloping, circular oscillators become one of the factors that restrict energy harvesting;

(2) The interaction between cylinders (serial and staggered) showed a good effect of oscillator synergy in the energy harvesting device. In recent studies, as expected, under the same controllable parameters, the power collected or converted by two series cylinders can be more than twice that of a single cylinder. In some experimental and computational tests, the power of two cylinders can reach 2.56-7.5 times that of a single cylinder;

(3) The use of PTC technology can maximize the range of the synchronization region. Its advantages are similar to those of oscillators with different cross-sections, as it expands the range of flow-induced vibration energy harvesting by enabling back-to-back VIVs and leaving no gaps within the tested flow velocity range. A cylinder with a smooth PTC surface can also provide similar power output as a rough cylinder, but at a slightly lower order of magnitude. This suggests that roughness is not necessary to promote higher power generation, but it can certainly be a good choice as an adjustment parameter;

(4)To date, velocity-based adaptive damping is the optimal solution. It mimics the natural response of a fish exchanging energy between a moving fluid and an oscillator. The introduction of adaptive damping allows for the utilization of energy while maintaining the oscillation range (VIV branch, transition to galloping, and galloping). Furthermore, adaptive damping reduces the initial velocity for energy harvesting and improves the performance of fluid kinetic energy conversion. At the end of galloping, as the flow velocity increases, the corresponding damping or utilized power reaches equilibrium, resulting in stable power and efficiency;

(5) In future research, whether a power generation device with nonlinear adaptive damping is beneficial to the conversion of electrical energy in the case of flow-induced vibration caused by mutual interference of multiple columns needs further exploration and research.

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