Autonomous Kite-Sailing Power Generation

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1. Abundant Offshore Wind Energy around Japan

Japanese Prime Minister Yoshihide Suga announced that Japan will reduce overall greenhouse gas emissions to zero by 2050. In order to achieve this pledge, larger amount of renewable energy resources should be developed. The most promising renewable energy seems to be offshore wind power, because Japanese islands are surrounded by vast oceans. Japanese Ministry of the Environment[1)] and New Energy and Industrial Technology Development Organization[2)] (NEDO) have estimated that offshore wind energy potential around Japan is approximately 1200 ~ 1500 GW. Moreover, this is the energy potential estimation confined to the nearshore sea areas within 30km distance from the homeland. As shown in Fig.1, offshore wind energy potential becomes higher in the offshore sea areas farther from the homeland. The wind energy in the offshore sea areas exceeding 30km far from the homeland is still more abundant, and it could supply a demand for overall electricity consumption in Japan.

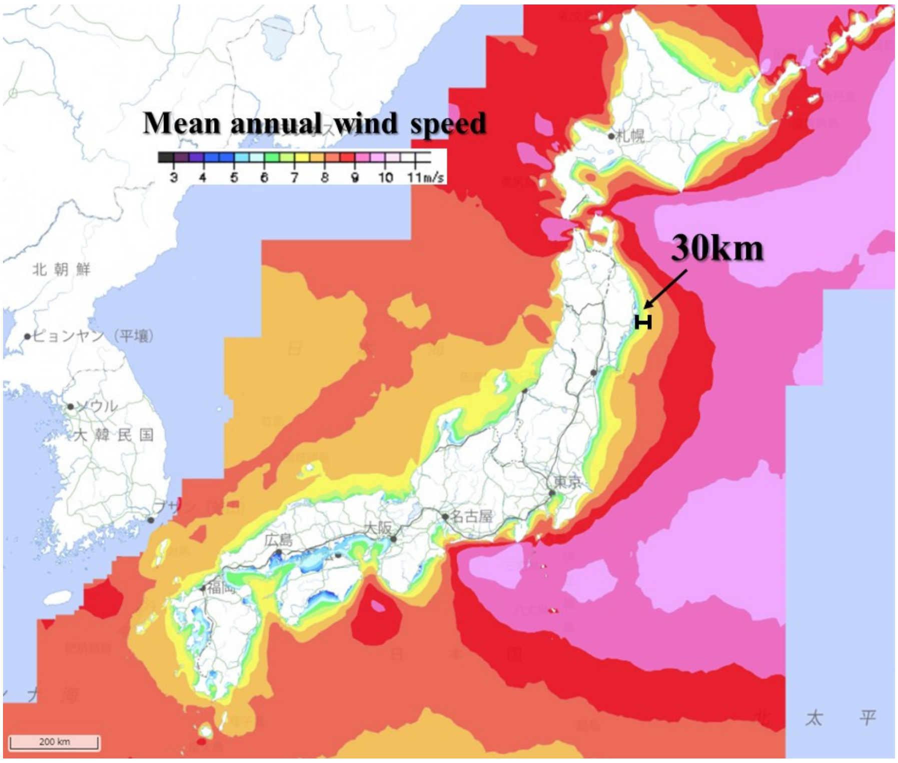

Fig. 1 Offshore wind energy around Japan[3)]

However, most of offshore wind turbines have been installed in nearshore sea areas within 30km distance from lands. Because laying longer subsea power transmission cables to farther offshore wind turbines raises the installation and maintenance costs significantly in addition to anchoring costs at deep waters. Meanwhile, there are many difficulties such as interference with fishing activities to install wind turbines in the nearshore areas. If we accessed to the abundant wind energy in the offshore areas exceeding 30km far from lands, we could avoid the interference with fishing activities and obtain sufficient energy to reduce overall greenhouse gas emissions to zero. In order to realize that, breakthrough technologies are necessary to offshore wind power generation.

2. Proposal of the Autonomous Kite-Sailing Power Generation

We have proposed the Autonomous Kite-Sailing Power Generation as a next-generation offshore wind power generating system shown in Fig. 2. The floating vessel sails exploiting the towing force induced by a kite capturing offshore wind. This kite is flown at high speed by describing a figure-of-eight trajectory in the air through manipulation of a pair of tethers connected to the kite. This high-speed flight amplifies the kite's towing force effectively. The longer the tethers are, the higher wind energy is obtained at higher altitude. Then the water current turbines mounted under the floating vessel generate electric power by exploiting the water current induced by the kite sailing. The generated electric power is stored in a battery inside the vessel instead of connecting to electric power transmission cables. The other way to store the generated power is converting to hydrogen gas by electrolysis of seawater. Without any anchoring or cable connection, the Autonomous Kite-Sailing Power Generation system is capable of moving around on the sea surface and generating electric power regardless of water depth and distance of electricity transmission. Accordingly, it can access abundant wind energy in the offshore areas exceeding 30km far from lands. Moreover, this system does not occupy any fishing area and hence not interfere with fishing activities.

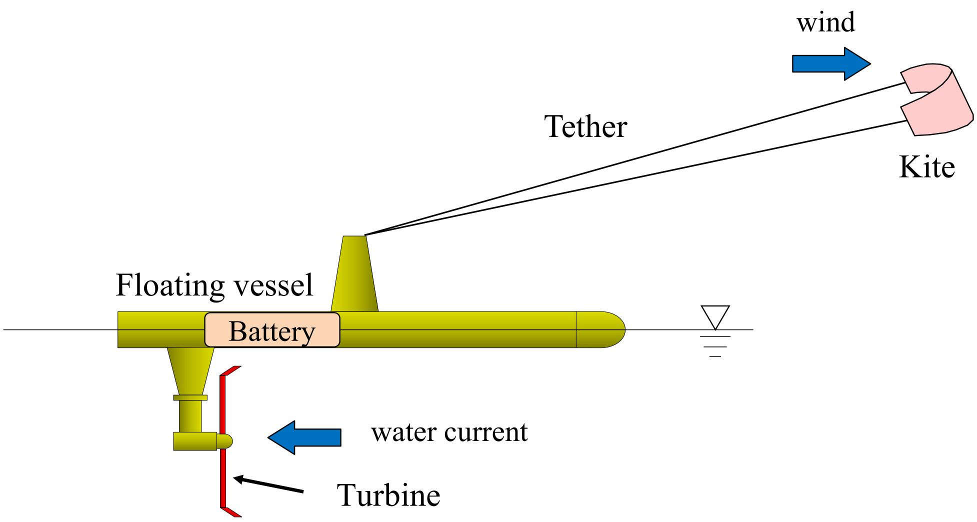

Fig. 2 The Autonomous Kite-Sailing Power Generation

The Autonomous Kite-Sailing Power Generation system generates electric power not directly from the offshore wind but from the water current induced by the offshore wind through the kite. In general, the electric powers generated by propeller turbines are proportional to the fluid density, the square of rotor diameter and the cube of fluid velocity. Although the fluid velocity of the water current is lower than the wind, the fluid density of the water is about 800 times higher than the wind. Accordingly, a smaller size of water current turbine is expected to generate electric power same as a larger size of wind turbine, and then the water current turbines are more compact in size than wind turbines. This contributes to reduce the manufacturing cost of the Autonomous Kite-Sailing Power Generation system.

The Autonomous Kite-Sailing Power Generation works as an unmanned surface vehicle. It generates and stores sufficient electric power in the offshore areas, and it autonomously return to its home ports to supply the electric power to lands. Then it goes autonomously to the offshore areas again to obtain more wind energy. This repetitive work of energy transport is conducted by the kite-sailing power without fuel to propel. Then the Autonomous Kite-Sailing Power Generation system becomes a kind of energy carrier and could achieve a low-cost energy transmission compared to laying subsea power transmission cables.

The advantages of the Autonomous Kite-Sailing Power Generation are listed as follows compared to conventional wind turbines.

- It can access abundant wind energy in the offshore areas exceeding 30km far from lands by using kite-sailing system without anchoring and connecting to power transmission cables.
- Its kite system can access higher wind energy at higher-altitude area than wind turbines.
- It does not interfere with fishing activities because it is not anchored and does not occupy any fishing area.
- It is more compact in size than wind turbines and generates electric power same as lager-size wind turbines.
- It can transport offshore wind energy to lands by its sailing system instead of high-cost subsea power transmission cables.

3. The DeepSky Concept

As mentioned above, the Autonomous Kite-Sailing Power Generation system is capable of carrying out long-term missions autonomously by sailing without fuel over a wide range of offshore areas. Therefore, it can be utilized for multiple purposes by equipping various devices and sensors as shown in Fig. 3. Moreover, by deploying a large number of the multipurpose Autonomous Kite-Sailing Power Generation systems and collaborating each other as a network, they can work as a common platform of various offshore infrastructures as follows.

- Offshore early-warning system equipped with weather observation devices for typhoon and tsunami
- Autonomous maritime security system equipped with surveillance devices for marine salvage, illegal fishing or maritime self-defense of isolated islands
- Autonomous submarine prospecting system equipped with sonars to explore scarce resources such as rare metal
- Offshore internet facility utilizing the high-altitude kite as a communication antenna
- Energy-saving offshore datacenter equipped with data server cooling by seawater
- Autonomous clean-up system for marine plastic debris
- Offshore charging station utilized for electric vessels

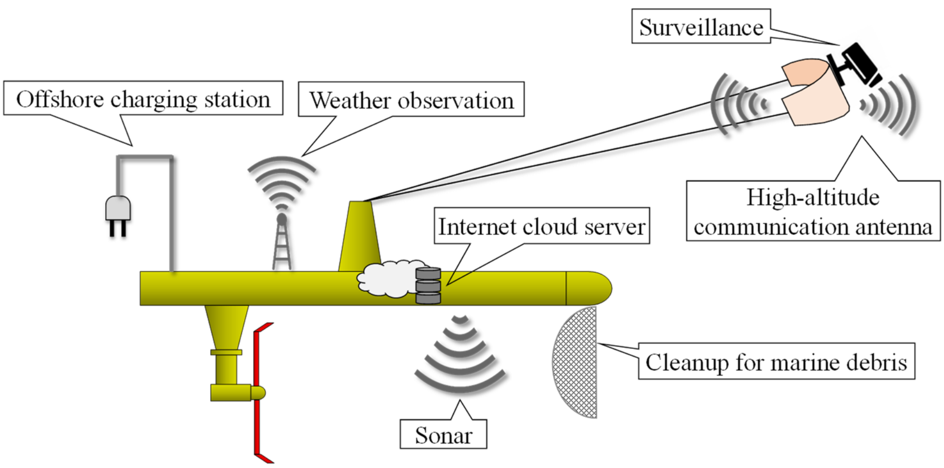

Fig. 3 The Autonomous Kite-Sailing Power Generation equipped with devices and sensors

The area of the exclusive economic zone (EEZ) in Japan is the sixth largest in the world, but it has not been utilized actively. The Autonomous Kite-Sailing platform can accelerate the high-degree application of this vast ocean space. If the above-mentioned offshore infrastructures were constructed on the ocean, various businesses exploiting oceanic big data obtained from them could be created. Moreover, the above multiplex businesses based on the Autonomous Kite-Sailing platform are expected to establish a more profitable and sustainable business model of offshore wind power generation.

We have propounded the “DeepSky” concept which aims to achieve energy self-sufficiency ratio of 100% by exploiting the sky-high wind energy over the deep ocean spaces based on the Autonomous Kite-Sailing platform. This also aims to change the unutilized vast ocean spaces to a virtual homeland through the common platform of the multipurpose infrastructures established by the Autonomous Kite-Sailing system. This platform contributes not only to achieve the reduction of overall greenhouse gas emissions to zero by 2050, but also to realize the Maritime Domain Awareness promoted by the Japanese government, which aims to gather and share various oceanic big data about forthcoming large earthquakes, incursion of foreign vessels, climate change and fishery resources.

4. Research and Development of the Autonomous Kite-Sailing Power Generation

(1) Similar energy conversion method based on kite flight

Airborne wind energy[4], which is a kite-based wind energy conversion method similar to the Autonomous Kite-Sailing Power Generation, has been developed in many European countries. The long tether of the kite is wound on a reel placed on the ground, and it is reeled out with the kite flown away. At the same time, a power generator attached on the reel rotates with the reel rotation and generates electric power. After the tether is reeled out to the end, reversely the tether is reeled in with the kite flown down. Although the energy is consumed to reel the tether in, the energy consumption can be minimized by reeling in with the kite flown down slowly. The other method of the air borne wind energy is to fly the kite with wind turbines installed on the kite. In this case, the installed wind turbine is restricted to lightweight, but it can generate electric power exploiting high-altitude strong wind power.

Fig. 4 Ship propulsion systems using towing kites[5][6]

Some ship propulsion systems using towing kites have been developed as shown in Fig. 4. These kites are controlled to describe the figure-of-eight trajectory and amplify the towing forces similarly to the Autonomous Kite-Sailing Power Generation. These kite-sailing ships have already been commercialized and succeeded to reduce fuel consumption of the ship propulsion. If water current turbines were installed to these kite-sailing ships, they could be equivalent systems to the Autonomous Kite-Sailing Power Generation.

Kim and Park[7] have proposed a kite-sailing power generation system similar to the Autonomous Kite-Sailing Power Generation. In their system, the kite is flown statically at fixed point in the air over the lateral direction of the ship. However, the lift force induced by such static kite is lower than the kite flown by describing the figure-of-eight trajectory. Furthermore, most of the towing force induced by the kite flown in the lateral direction of the ship does not contribute to propel the ship. Accordingly, the energy harvesting efficiency of their system seems to be lower than the Autonomous Kite-Sailing Power Generation.

(2) Performance simulation of the Autonomous Kite-Sailing Power Generation

We have developed the kite flight simulator[8] to examine the energy harvesting performances of the Autonomous Kite-Sailing Power Generation. This simulator is based on the coupling equations between the kite flying along a figure-of-eight trajectory and the vessel sailing by the towing kite. As shown in Fig. 5, the kite with a wingspan of 20m and a chord length of 5m is employed in the simulation. NACA4415 airfoil is used for the wing cross-section of the kite, and the wing has a span-wise curvature with a central angle of 90°. We assumed that two water current turbines with a diameter of 5m are mounted under the vessel with a weight of 100ton and they are towed by the kite. These specifications of the vessel and the turbines are determined by considering the SR250 floating tidal turbine of Orbital Marine Power Ltd[9]. The specifications used in the simulation are listed in Table 1. Wind speed is assumed to be 15m/s at 10m altitude and increase with altitude according to logarithmic law.

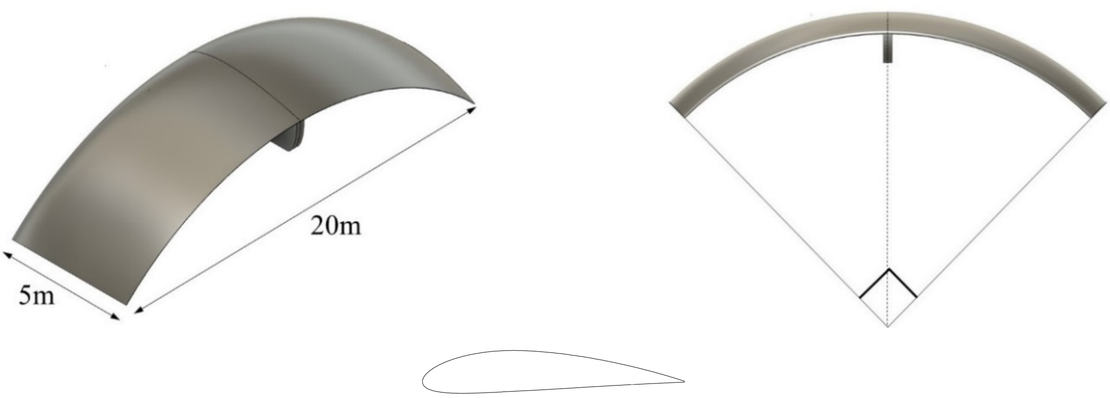

Fig. 5 Kite and its cross-section geometry used in the simulation

Table 1 Kite, tether, vessel and turbine specifications used in the simulation

kite	mass	77 kg
	wing area	100 m^2
	wingspan	20 m
	chord length	5 m
tether	length	200 m
	diameter	0.03 m
	drag coefficient	1.2
vessel	mass	100 ton
	underwater cross-section area	3.14 m^2
	drag coefficient	1.0
turbine	number of turbines	2
	total swept area of rotor	39.27 m^2
	power coefficient	0.35

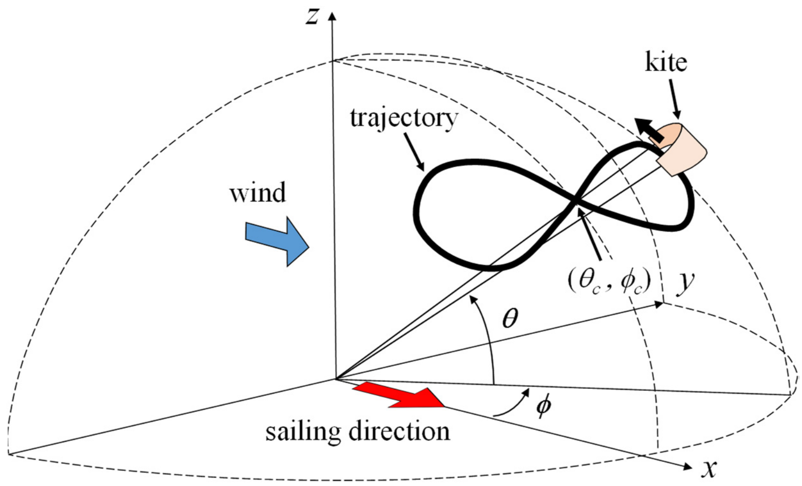

Fig. 6 Schematic of the simulation for the Autonomous Kite-Sailing Power Generation

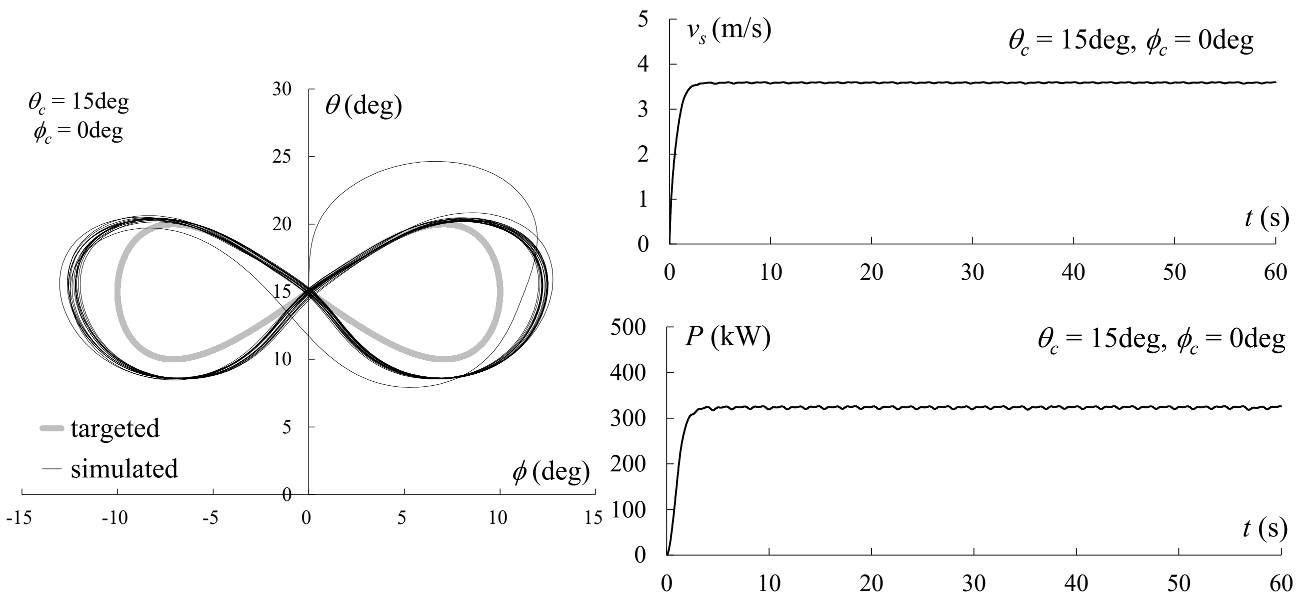

Fig. 7 Example of the simulation results in flight case of θ_c= 15°, ϕ_c= 0°

In the simulation, the kite flies on the surface of a quarter sphere in the air, and its position is denoted by elevation angle θ and azimuth angle ϕ as shown in Fig. 6. Then the center position of the figure-of-eight trajectory of the kite is denoted by θ_c and ϕ_c. The directions of the natural wind and the sailing path of the floating vessel are assumed to coincide with the direction of ϕ = 0°. Fig. 7 is an example of the simulation results in the trajectory case of θ_c= 15° and ϕ_c= 0°. The flight direction of the kite changes with the kite's roll angle adjusted by manipulating a pair of tethers connected to the kite. Fig. 7 shows that the kite can fly close to the targeted trajectory. At the same time, the floating vessel velocity v_s and the power P generated by the turbines are v_s= 3.6m/s and P= 324kW on average, respectively. This is just an example to show the energy harvesting performance of the Autonomous Kite-Sailing Power Generation, and the performances could be higher if larger sizes of kites and turbines were employed.

(3) Development of the Hydro-VENUS turbine based on flow-induced oscillation

We have been developing the Hydro-VENUS (Hydrokinetic Vortex ENergy Utilization System) in Fig. 8 as a water current turbine appropriate for the Autonomous Kite-Sailing Power Generation. The Hydro-VENUS is a pendulum-based energy converter exploiting flow-induced oscillations. When a circular cylinder pendulum[10)11)] is employed for the Hydro-VENUS, the vortex-induced oscillation occurs due to the Karman vortices shedding periodically from the pendulum. However, the amplitude of the vortex-induced oscillation is relatively small, and then the harvested energy is also small. On the other hand, the galloping oscillation, which is still stronger than the vortex-induced oscillation, occurs and can harvest higher energy when a semi-circular cylinder pendulum[12)] is employed for the Hydro-VENUS.

The galloping is a self-excited oscillation induced by the shear flows separated from a solid body. As shown in Fig. 9, the shear flows are separated from the sharp edges on the both sides of the semi-circular cylinder cross-section. These separated shear flows incline toward the opposite direction of the pendulum velocity. These asymmetric flows cause pressure difference between the both sides of the pendulum surface. This pressure difference involves hydrodynamic forces perpendicular to the flow direction, and accelerates the pendulum oscillation. This acceleration promotes the flow asymmetricity and increases the pressure difference further. Accordingly, the hydrodynamic forces acting on the pendulum and the pendulum velocity continue to rise each other. This feedback amplification between the hydrodynamic forces and the pendulum velocity causes self-excited large-amplitude oscillations of galloping.

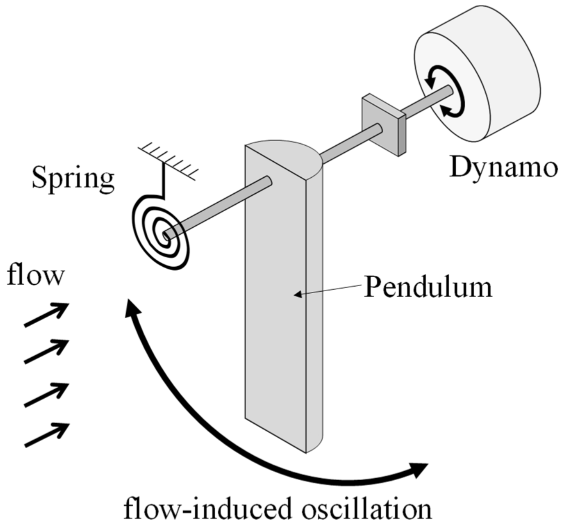

Fig. 8 Schematic of the Hydro-VENUS

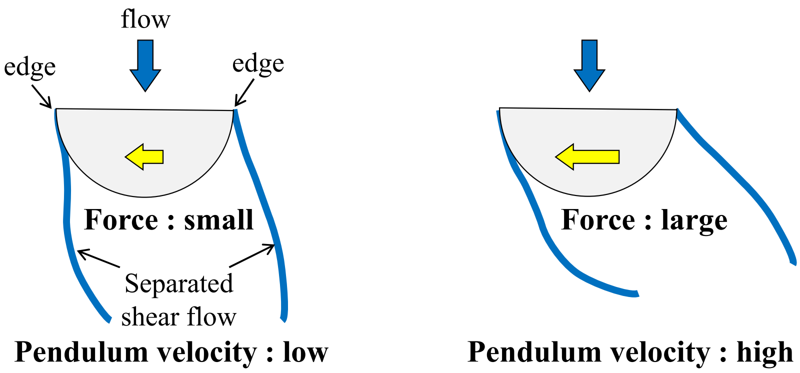

Fig. 9 Mechanism of galloping oscillation

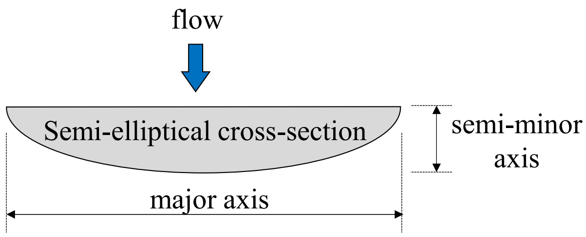

Fig. 10 Semi-elliptical cross-section with aspect ratio of 6

According to the previous studies[13)14)] about the cross-section geometry of the Hydro-VENUS pendulum, it has turned out that semi-elliptical cross-section with an aspect ratio of 6 in Fig. 10 is the most effective to induce large-amplitude galloping oscillations and achieves 10 times higher energy harvesting performance than the circular cylinder pendulum. The amplitudes of the semi-elliptical cross-section pendulum in galloping oscillation exceed 360° and reach several rotations when the spring constant in Fig. 8 is small. It is found that one-way rotation ultimately occurs in the pendulum without the spring. This rotational pendulum works as if it was a conventional propeller rotor. But its mechanism of the rotation is absolutely based on the galloping caused by the feedback amplification between the pendulum and the separated shear flows around the pendulum.

It is revealed that this Hydro-VENUS rotor with semi-elliptical cross-section shows the high energy harvesting performances equivalent to the conventional propeller turbines with airfoil blades[14)]. In addition, this Hydro-VENUS rotor is capable of rotating in both the forward and the reverse direction quite differently from the conventional airfoil propellers. Thus, it can keep rotating and generating powers by changing the rotational direction in accordance with the flow conditions even in the strongly turbulent flows. This direction-changeable rotation of the Hydro-VENUS rotor is also effective to avoid winding of driftage around the rotor. In addition, the start-up performance of the Hydro-VENUS rotor from fully stalled static state is expected to be high because of the feedback amplification mechanism same as the galloping. The Hydro-VENUS pendulum is a columnar body with uniform cross-section and without twisting angles. Accordingly, its three-dimensional shape is much simpler than airfoil blades of conventional propellers. Then it is easy to manufacture, and its manufacturing cost is expected to be low. It is also easy to reinforce the inside space of the pendulum with a small number of structural elements, and hence it is useful as a light-weight and high-strength turbine blade.

5. Future Tasks of Research and Development

In the Autonomous Kite-Sailing Power Generation, the kite is controlled to describe the figure-of-eight trajectory in the air by manipulating a pair of tethers automatically. In order to control the kite flying at high speed, it is necessary to control the tether actuator in real time by measuring the kite position and wind speed with sensors constantly. In order to achieve optimum control, it is important to reduce the effects of errors and time delays in the controls and measurements. Various automatic kite control systems have been developed in the field of Airborne Wind Energy[4)], and some of them have already been commercialized[5)6)15)]. Although some autonomous navigation systems[16)17)] of vessels have been developed and commercialized, autonomous navigation using the kite-sailing system is necessary in the future.

The floating vessel with water current turbines of the Autonomous Kite-Sailing Power Generation has to maintain stable attitude under the various conditions of sea surface waves, thrust forces acting on the turbines and towing forces induced by the kite. Submersible, semi-submersible and wave-piercing floating vessels seem to be useful for these purposes. Also, various floating type tidal turbines[18)19)20)21)] have been developed and could be diverted to the Autonomous Kite-Sailing Power Generation. We have been developing the floating type turbine with the Hydro-VENUS rotor as shown in Fig. 11. In addition, the battery technologies stably workable in the harsh offshore environments are also necessary.

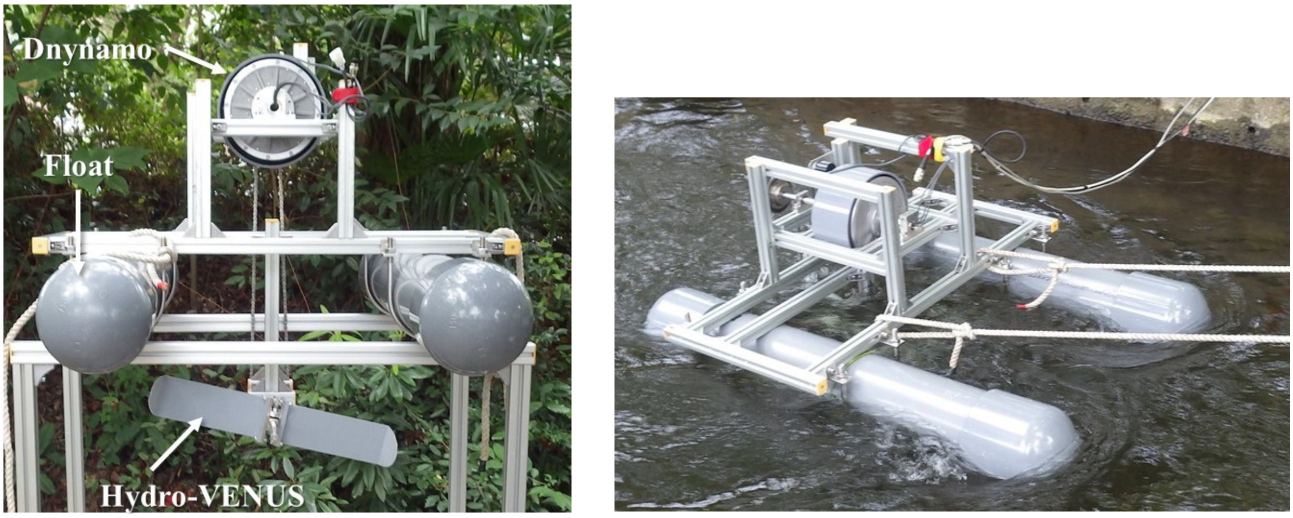

Fig. 11 Small-scale model of floating type turbine with the Hydro-VENUS rotor

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