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# Wave Power Converter Pendulor with Hybrid H.S.T.

Tomiji Watabe[1] and S. D. G. S. P. Gunawardane[2]

*1. T-Wave Consultant, 5-23-3, Misono, Noboribetsu 059-003, Japan*

*2. Dept. of Mechanical Engineering, Faculty of Engineering, University of Peradeniya, Peradeniya 20400, Sri Lanka*

**Abstract:** This Pendulor, wave power converter, was invented to be robust towards storms. The key is Hybrid H.S.T. for generator driving by a higher the speed and a smaller the torque of the piston pump which can do over 360 degrees rotation free of the pendulum motion. This idea will bring the non-shock operation to the moving body type wave power conversion and when the Pendulor applies with the antenna principle, it will have a possibility to convert safe and cheap electricity from the ocean by this technology.

**Key words:** Ocean wave power, Pendulor, H.S.T., hybrid, large plant.

## 1. Introduction

Muroran Institute of Technology Japan developed the wave energy converter Pendulor 39 years ago. The research advanced well at the beginning but faced a fundamental problem on the survivability towards storms. Since the original Pendulor depends on moving body type energy conversion, the system must have a stopper for the pendulum to keep the stroke within a limit, in any type of operation of energy conversion [1, 2]. The stopper should be a sockless for the stopping of the massive Pendulum. If we cannot pass this situation, the dream to make electricity from the ocean waves would be impossible. This new Pendulor has changed the system completely safe with no stopper [3]. The Pendulum can rotate over 360$^{o}$ both directions freely by applying with the new hybrid H.S.T. for generator driving. Plural number of piston pumps rotates increased speed by a step-up gear to deliver much oil with all. The system shall be able to be applied for a large Pendulor to improve the cost saving (three patents pending).

## 2. Birth of the Ocean Waves and Use of Them

Blowing wind on the ocean excites the sea water at the surface so that there appears periodical moving of the water (ripples); birth of the waves. The growth of the sea waves depends on the wind power, lasting the blowing time and along to a place follows to the wind pass away from beginning and lasting to the final place. It tells that the waves are phenomenon altered from the wind energy, and it propagates from the birth place, as it to be travelling waves. They are classified themselves within near sized waves together while travelling through such a long distance. Therefore, utilization of the wave energy, applied with the antenna principle, it can be such a long distance (Muroran Institute Technology took the principle from the beginning stage [4]). For development of the large Pendulor, driving it with energy rich waves was studied from a basic view point. The reason is that the Pendulor must do resonant operation with the incident waves and the generator load condition must be adjusted in coincide with the impedance of the Pendulor device for the optimal driving. Therefore, the Pendulor study cannot do anything without understanding on the incident waves for optimization of the wave power conversion. Fig. 1 [5, 6] is the first floating type Pendulor which has been studied by Korea after Muroran I. T. closed the study in 2000. The device of floater has applied new idea. (1) Floater is stable with a damping action by wave force in three directions.

**Corresponding author:** Tomiji Watabe, Dr., consulting engineer, former professor, research field: ocean wave energy.

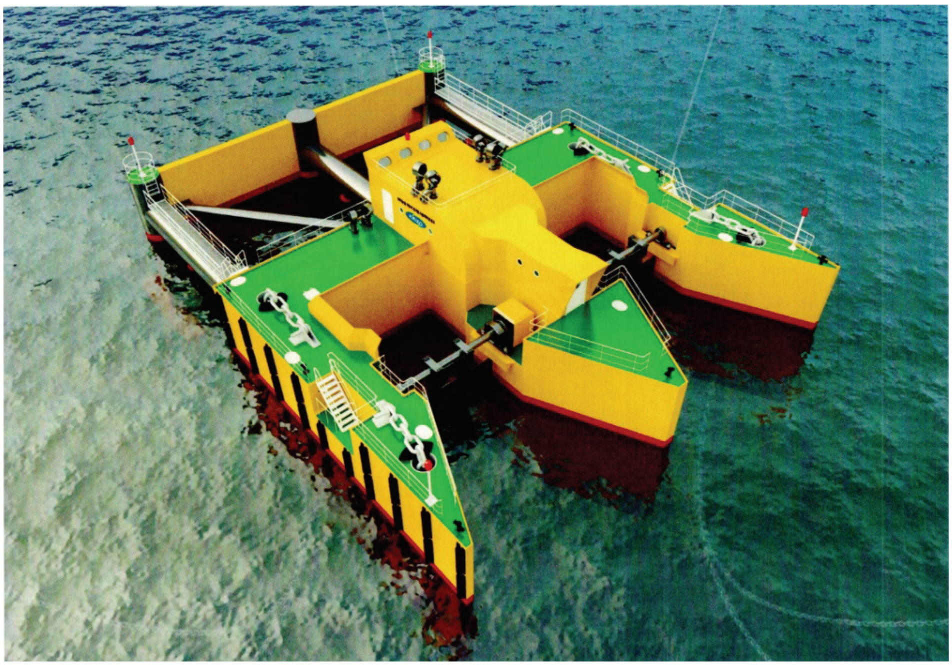


**Fig. 1 Floating Pendulor 300 kW, developed by, KRISO & YOOWON, Korea.**

(2) Optimization control of the wave power conversion. (3) Giant Rotary Vane pump direct coupled with the Pendulum. (4) Oil seal fits to the large pump. Japan created the soft of the System and Korea built the Power Plant of Pendulor [7].

## 3. Wave Power Density of the World

Fig. 2 shows the wave energy distribution, investigated by US Dept. of ENERGY by kW/m. The department estimated of the world wave energy potential; that is at 2 or 3 million MW. In favorable location, the wave energy can average 40 MW/km (= 40 kW/m of coastline) [8]. Comparing with the power density of Japan and the world, Japanese one is only 1/3 of the world. Nevertheless, the giant level typhoon frequently attacks Japan with strong power of storm of 10 times or more of the normal wave power. The Pendulor must survive towards them with not such the strongest machine but a clever and inexpensive one. The machine lets the dangerous waves go back to the sea as they do nothing harmful to the Pendulor.

## 4. Wave Power for Large Pendulor

Considering the magnitude of the wave energy potential on the Earth, we must pay attention to the big energy converter driven by high energy density waves. Here introduces an interesting study on the waves which are grown by several wind conditions. Since the glowing wave height and its period can be calculated when the wind speed and the fetch length are given, applying with the data shown in the chart (Fig. 3) [9]. The authors tried some investigations to find preferable waves which are good for driving the large Pendulor. Figs. 3 and 4 show the wave height: $H_{1/3}$ (m) and its period: $T_{1/3}$ (s) at given wind speed (m/s), blowing duration (hour) and distance: (Fetch length, km). In case of 10-hour wind blow with several wind speeds, glowing wave heights estimated are shown in Figs. 4 and 5 [9]. The wave height: $H_{1/3}$ increases as wind speed being higher. For the wave period: $T_{1/3}$, it becomes longer (by slower wave motion) excited with the higher blowing wind. It means the wave motion changes slower as the blowing wind to be stronger. Therefore, when a large Pendulor is driven by energy rich waves, the richer the energy density, the operating condition of the Pendulor becomes the slower speed and the bigger torque operation. This result tells us an important direction

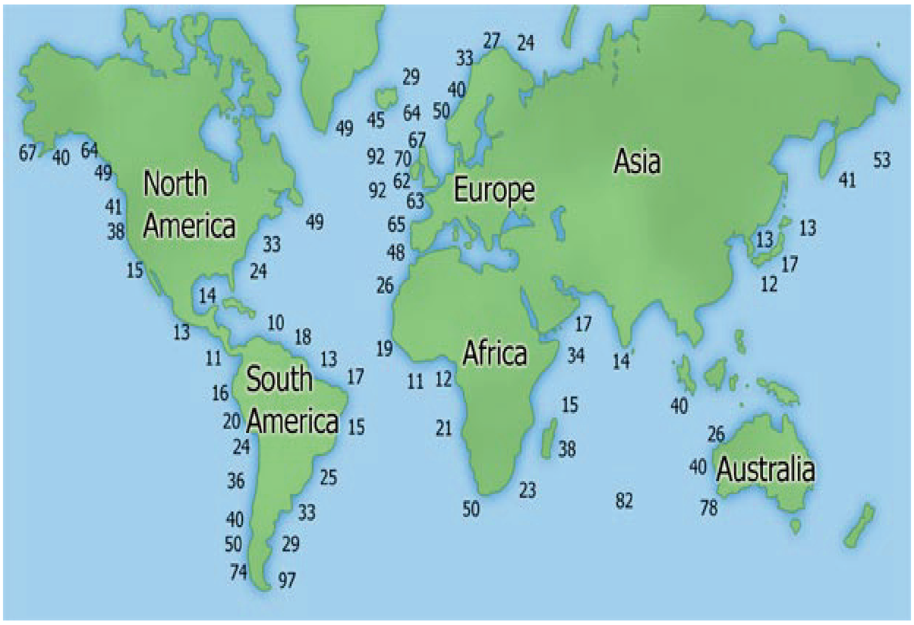



Fig. 2 Wave power distributions in the world with the unit kW/m (US Dept. of ENERGY).

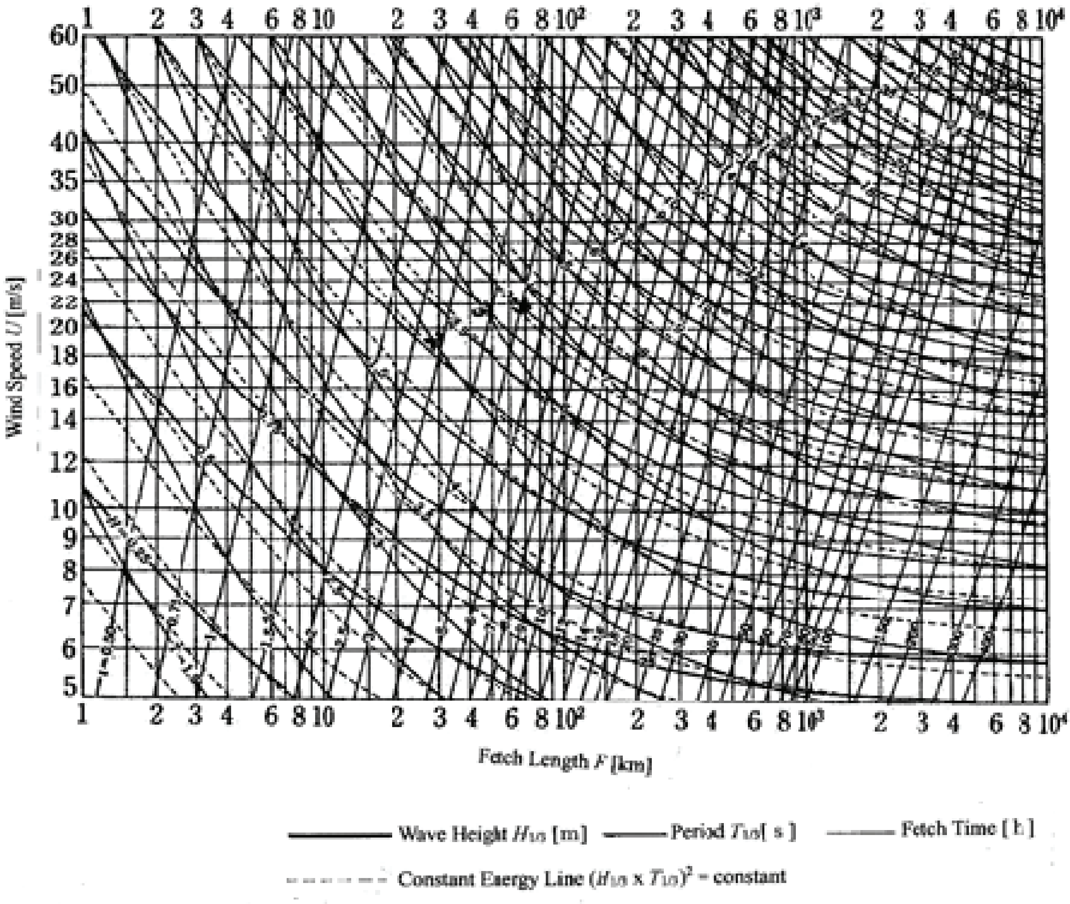



Fig. 3 Wind-wave forecasting curves of deep water.

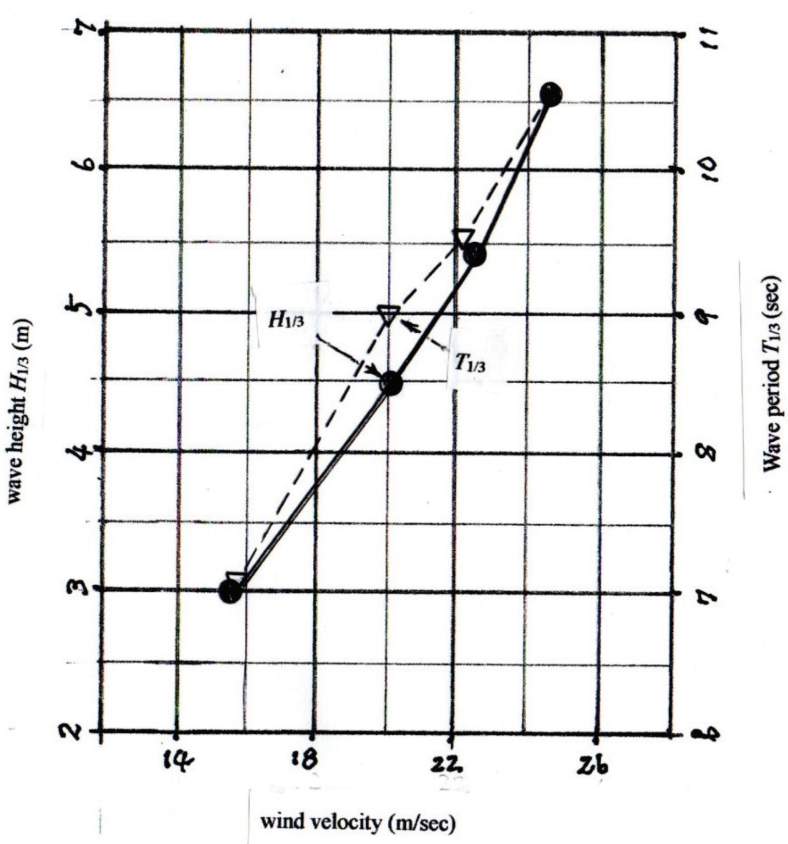



**Fig. 4 Period change by growth of wave.**

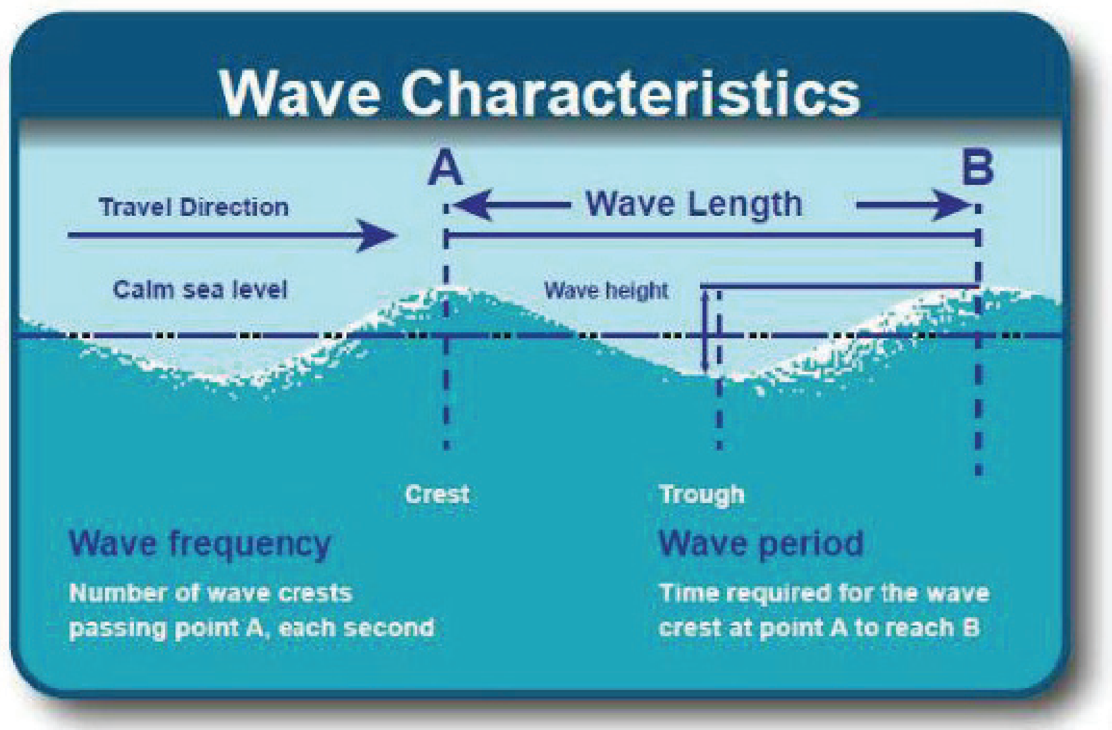



**Fig. 5 Wave characteristics relation between blowing wind on the sea and glowing waves.**

to challenge to the wave energy utilization with a large converter, the system must overcome the slower speed and the greater torque load operation. The authors decided to attach to this study with new ideas: shown here. New ideas for the large Pendulor: (1) Survival to the Storm by no-stopper ± 360° free rotation, (2) Invention of, hybrid H.S.T. for Generator driving, and (3) piston pump can work at the condition, well.

## 5. Experience on System Survivability

Since the wave energy conversion depends on the reciprocal wave motion, the action parts by waves must be limited even when the device encounters storms. The wave power of storm would be over 10 times greater level than the normal, the shock by impingement to the stopper often offers a damage situation to the system. During sea operation of a Pendulor, we experienced three times of accidental breaking of the flapper legs by impingement between the stopper and the legs [10]. The happening gives us a hint to avoid the trouble; by not improving the legs stronger but change the condition safer; by no use of the stopper. We selected the hybrid H.S.T. system for the Pendulor which requires no stepper as shown in Fig. 6 [11]. In Fig. 6, a single Pendulum drives four sets of geared piston pumps of the HST which drives a generator. Since the gear is to be speed up use, it drives the four pumps with increased speed with divided power of 1/4 each, so, the displacement of the pump unit becomes the value shown in Eq. (1).

$$D_p = D_o \times (\, power\ ratio\ devided) \times z_p/z_g \quad (1)$$

where, $D_o$: displacement of the pump when it is driven directly. In a case of 4 sets of pumps with teeth number of the pinion: $z_p = 7$ and teeth number of the gear: $z_g = 70$, $D_p$ takes the value shown by the Eq. (2), that is the case of Fig. 6.

$$D_p = D_o \times 1/4 \times 7/70 = 0.025\, D_o \quad (2)$$

This result means that the system of Fig. 6 can reduce the pump capacity required drastically, comparing with the former system of one set pump. The hybrid H.S.T. of Fig. 6 has no stopper because of the system permits over 360° rotation of the pendulum in either direction. The pendulum motion amplitude: $\theta_a$ is shown by Eq. (3) as a function of the incident wave height: $H$ [1].

$$\theta_a = \frac{k_0 z_0}{4\, y_0 \sinh k_0 h} \times \frac{H}{2} \quad (3)$$

$$Z_0 = \sinh 2k_0 h + 2k_0 h \quad (4)$$

$$Y_0 = k_0 l \sinh k_0 h + \cosh k_0 h - 1 \quad (5)$$

where, $k_0$: wave number, $H$: wave height and $h$: water depth, $l$: distance between the center of pendulum shaft and the water surface.

Piston pump of Fig. 6 is non rotating type. Its feature is much simpler than the rotary type piston pump and being strong towards the cavitation and dynamic load because of the tiny moment of inertia. The pump can be inherently fit to the reciprocal rotation as well.

## 6. Improvement of the Survivability of the Pendulor

The cause of damage on the wave energy converter observed was by shock load most, not only on the Pendulor but also the Pelamis [11] (Fig. 7) and, the Oyster [12] (Fig. 8). The shock load worked likely both places with the stoppers and the mechanical power-transmission where small gaps existed between the parts faced with two of them which cannot be combined into one part. The gaps make shocking impingement. In case of impingement at the stopper, there relates often with big force by collision. Therefore, some components of the stopper are damaged frequently. For instance, the tightening bolts of the stopper to be loosened at even primary condition then the all bolts were broken away to the final stage. The incident lets us make the mind, to improve the power take off components to be improved for being reliable much more. The decision is, to exchange the design principle with no use of the stopper. This idea has been realized by the hybrid H.S.T. developed shown in Fig. 6.

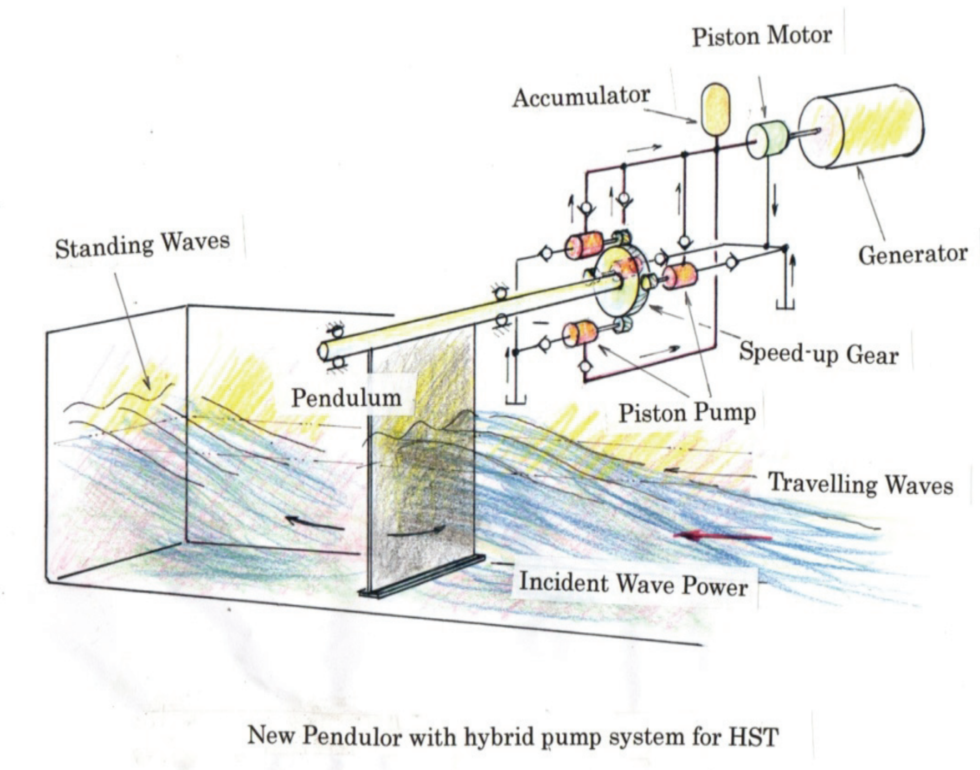



**Fig. 6 Principle of the pendulum combined with the Hybrid H.S.T. (Patent app. 2017-01 5068).**


**Fig. 7 Typical W. E. converter: Pelamis UK.**

## 7. Design of the Hybrid H.S.T.

Fig. 9 is a trial design with 16 pumps to make a set of geared pumps for the hybrid H.S.T. This idea is for an MW class study on the large Pendulor with 16 pumps incorporated under the speed ratio: $z_g/z_p$ = 120/9 = 13.33. It seems one of the balanced features from the engineering and the economic stand point. The case shown in Fig. 9, the pump speed is increased in 13.33 times higher than the case of no gear driving. In 16 pumps of the displacement $D_p$ each is shown by Eq. (6).

$$D_p = D_o \times 1/16 \times 6/120 = D_o \times 1/320 \qquad (6)$$

Therefore, the case of Fig. 9, the 16 pumps have the 320 times small displacement though, it is enough for the pumps of the Hybrid H.S.T. Despite of such as 16 pumps drive in parallel, each the load is divided into each the pump exactly by the error absorption effect into the teeth pitch error of the pumps. For design on the 7 teeth pinion of the Hybrid H.S.T, there is no fear

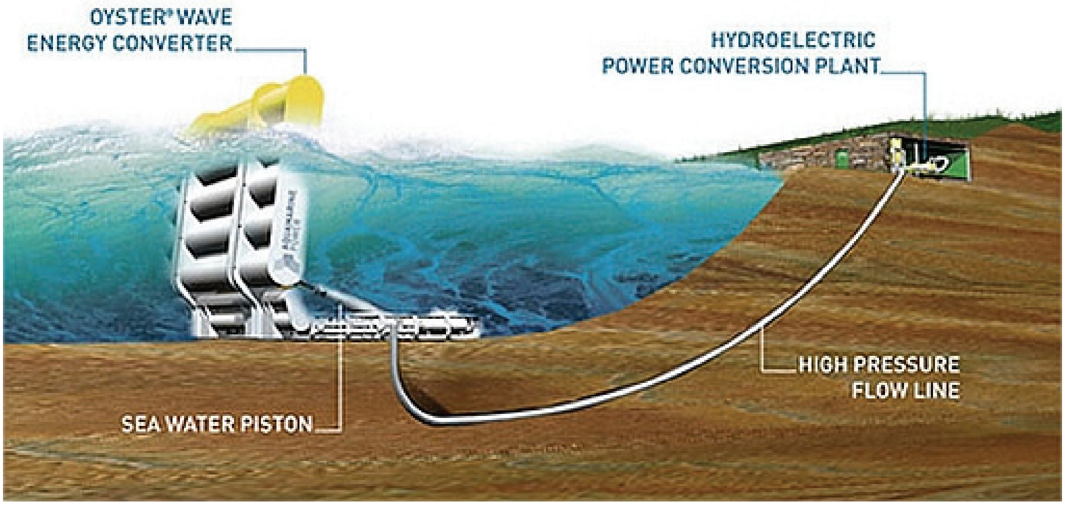
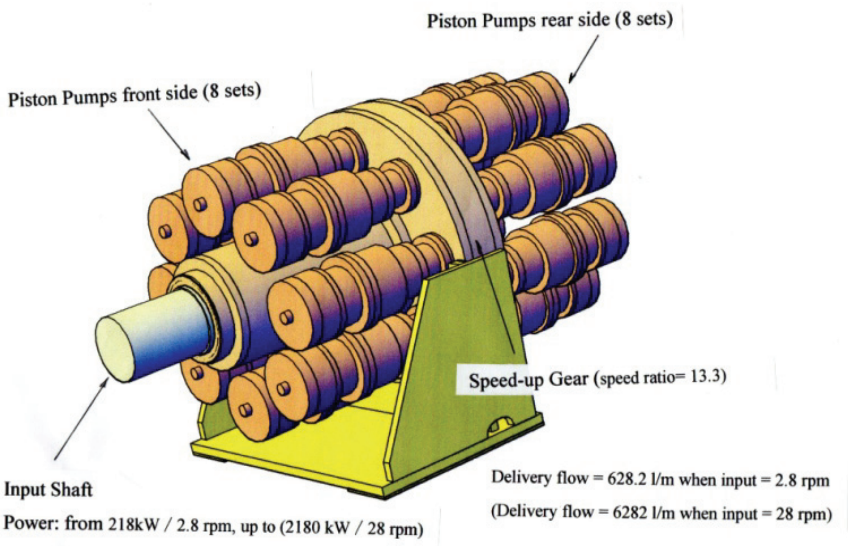
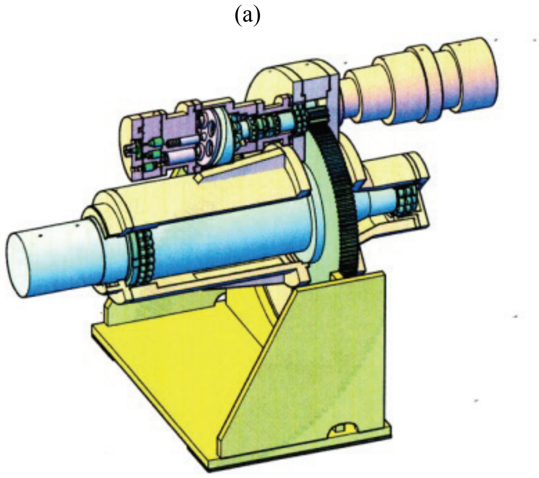



**Fig. 8 Inverse pendulum converter Oyster UK uses water power transmission.**




(a)



(b)

**Fig. 9 (a) Geared piston pump set for 1 MW class (Patent App. No. 2014-173194, 2014, T-Wave); (b) Geared pump set shown inside.**

of appearance of an under cutting trouble by the interference towards the 7 teeth form pinion. That is an allowable limit condition with the sharpened teeth tips (the larger the speed ratio: $z_g/z_p$, the hybrid H.S.T. can be made smaller mass and dimension).

For the gear lubrication of the condition (high tooth load Fig. 9b slow speed operation) is not easy for safety operation, so that some attentions written below (1)-(3) are useful:

(1) The teeth are treated with the hardening by nitride process, then polished by lapping finish to make 0.5 μm flatness on the contact teeth surfaces. The error of the tooth profile and the pitch are not important in case of slow rotation (Under 100 rpm).

(2) For the teeth strength, especially to the contact pressure, we should pay attention carefully (oil film thickness at the contact point etc.).

(3) For the gear design, the contact points motion by a pure rolling each other teeth as perfect as possible. This kind of care makes steady lubrication by EHL (Elastic & Hydro-Dynamic Lubrication). This Hybrid H.S.T. idea can be used also for Wind Turbine. The reason is, the case of wind turbine drives high speed generator with very slow speed turbine [11].

## 8. Piston Pump

Fig. 10 is the pump designed for the Hybrid H.S.T. for study purpose of a large Pendulor. It belongs to non-rotating axial piston pump group of five pistons in a pump considering the abnormal slow speed operation. The pump can be used as a variable type or fixed one when the suction check valves are kept in open or in close. In case of the large Pendulor (and Fig. 9 is the Hybrid pump for it [2]), the displacement $D_p$ required for the Hybrid piston pump is shown by Eq. (6).

## 9. Study on the Piston and the Shoe

The large Pendulor with the hybrid H.S.T. faces a situation that tells us the Wave Plant would be instable more if the piston assembly is exposed under an abnormal slow speed and a high load operation with the conventional type slipper. Therefore, we decided to make the Hybrid H.S.T. be stable better with the new idea to improve the static bearing for the axial piston slipper (Patent Pending).

When a large displacement ($D_P$ = 100 lit/rev) pump is running with speed: $n_p$ = 100 rpm, it delivers oil,

$$Q_{th} = D_p \times n_p = 10{,}000 \text{ l/m} \qquad (7)$$

where, $Q_{th}$ is the theoretical oil delivery. $Q_{th}$ is proportional to speed: $n_p$, and the actual flow: $Q_p$ is shown by Eq. (8),

$$Q_p = Q_{th} - \Delta q \qquad (8)$$

where, $\Delta q$: leak flow.

Leak flow $\Delta q$ is proportional to the delivery pressure: $p$ and time: $t$ of the pump operation. Since the clearance located between pressure difference in the pump where being a path of the leakage, the passing area would be proportional to the pump dimension.

The author experienced an observation of the swash plate type piston machine which happened metal contact whenever starting. The friction by the metal contact accompanied with a fair amount of oil leak which made the condition worse, too. Fig. 11 is a piston and a shoe of the axial piston pump/motor invented to overcome the energy loss by the metal contact at slow motion. The principle is applied both in the piston and on the shoe as shown in Fig. 11. On the surface of the static bearing (piston and shoe), there are some thrust control pools of which pressure is controlled by the outer load, irrespective of running speed. The oil pressure at a place is the function of flow-in and flow-out oil volume, the external load controls the pressure of the control pools, and the pool pressure adjusts the lateral clearance of the bearing pads non-uniformly. So, it produces the bearing action change, no metal contact (Patent Pending). The thrust pools locate on the piston surface, too. The pool pressure is controlled when the load balance approves the lateral load and the reaction relationship caused by the oil pressure. Fig. 11 shows that the piston

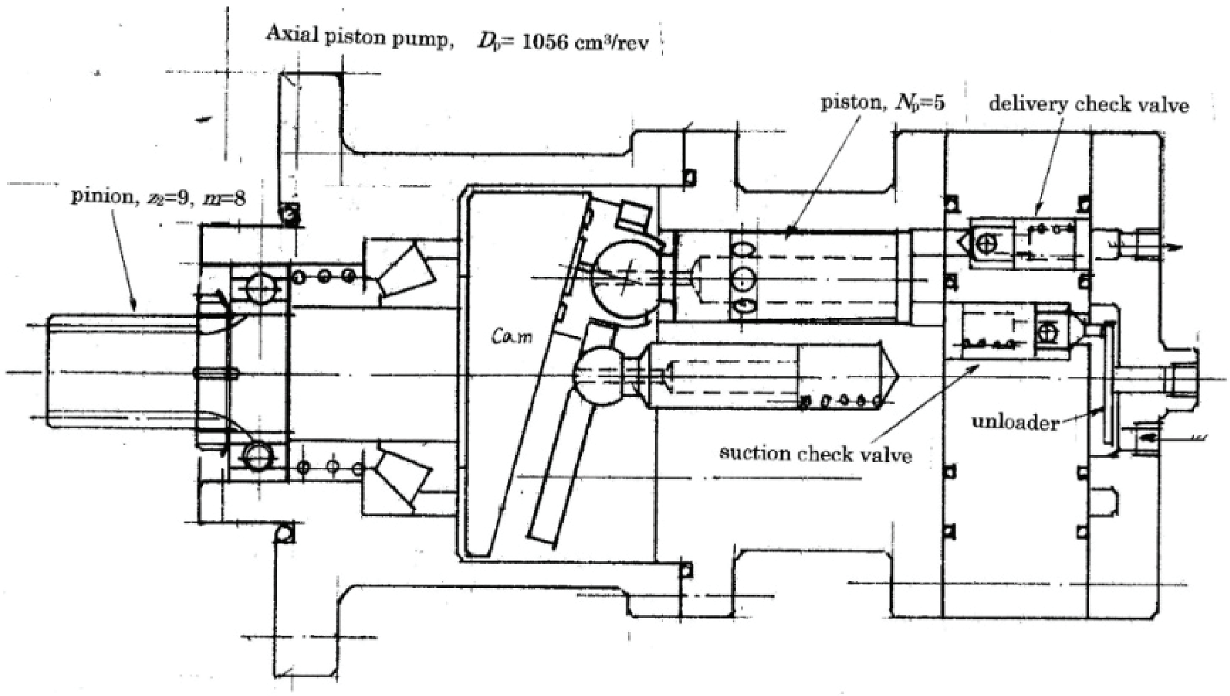



**Fig. 10 Piston pump for hybrid H.S.T.**

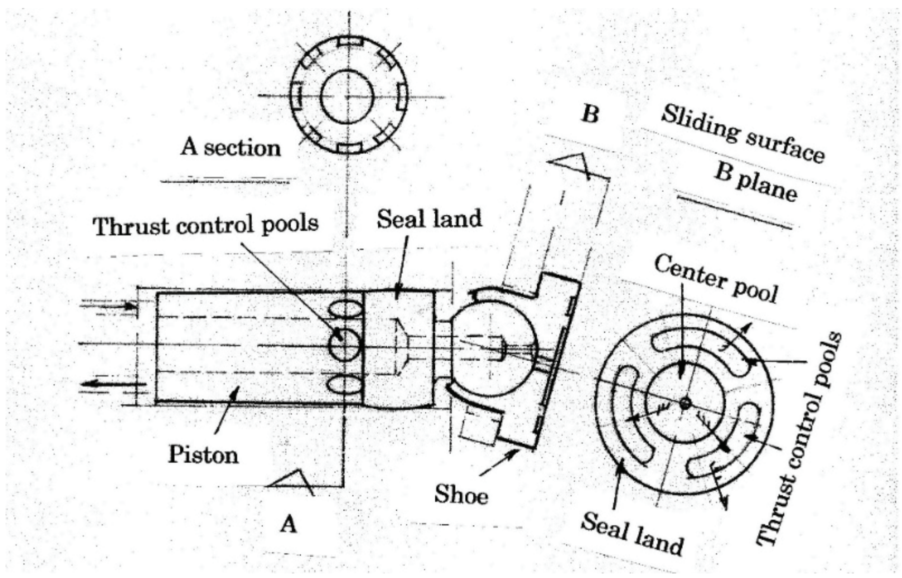



**Fig. 11 Piston and shoe with self-balancer (Pat. Pending).**

**Table 1 The wind-waves grown by several wind speeds.**

| Case No. terms | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Wave height, $H_{1/3}$ (m) | 3.0 | 4.5 | 5.4 | 6.6 |
| Wave period, $T_{1/3}$ (s) | 7.0 | 9.0 | 9.5 | 10.5 |
| Wind speed (m/s) | 15.5 | 20 | 22.5 | 25.0 |
| Duration (H) | 10 | 10 | 10 | 10 |
| Minimum fetch length (km) | 40 | 52 | 58 | 65 |

clearance is controlled to move the piston center. Therefore, when the pressure is bigger, the lateral force becomes the bigger. The principle:

The piston configuration is located right to left, ball formed joint, clown formed seal, pools located on the taper formed guide. The piston can rotate in the lateral gap by the tapered guide which affects pressure change of the pools.

When a normal vector pushes the shoe at the sliding center shown in Fig. 11, one force vector component of up direction, drives the piston by anti-clock wise moment. Therefore, on the taper part of the piston, upper side gap becomes larger and lower side one becomes minimum.

Then, this change makes the pressure of upper side pool the higher and lower side pool the smaller. The pressure difference between up and down side pushes the piston down direction which acts force to the piston with the opposite direction of the load. If the oil pressure cancels the piston load, the minimum friction loss would be possible applied with this technology (Patent Pending).

## 10. Conclusions

The idea of Pendulor with the hybrid H.S.T. can be concluded as shown bellow.

(1) The new idea was reported here that the Pendulor can be survival against the storm with the hybrid H.S.T. assembled into the Pendulor system.

(2) This idea contributes to the practical wave energy conversion not only being survival in the storm but also opening a new possibility to develop MW class large Pendulor by EHL (Elasto-Hydro Dynamic Lubrication) technology for the high torque and slow speed operation.

(3) The axial piston pump with a small moment of inertia, can improve the Pendulor efficiency at high torque slow speed operation. This idea on the hybrid H.S.T. is suitable for the large wind turbine application, too.

(4) The converter on the moving body type, pelamis and oyster, the cause of failure was studied to overcome the problem in the future.

## Acknowledgment

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