



WAVE POWER CONVERTER PENDULOR WITH HYBRID H.S.T.

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Abstract. This Pendulor: wave energy converter has been invented to be robust towards storms. The key is Hybrid H.S.T. for generator driving with changing the speed and torque of the piston pump which can work easier under over 360° free rotation of the Pendulum motion (Primary Energy Absorber). The idea has brought non-shock operation in the moving type wave energy conversion. It shall also give us a future possibility to present all the people with Cheap Electricity generated from the Ocean by this technology.

Keywords: Ocean wave power, Conversion, Pendulor, H.S.T., Hybrid, Large power plant, Pelamis, Oyster.

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 be kept the stroke within a limit, in any time of operation⁽¹⁾⁽²⁾. The stopper should be a shockless at the stopping of the massive Pendulum. If we cannot solve this matter, 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° both directions freely by applying with the new Hybrid H.S.T. for generator driving. Plural number of piston pumps driven by one speed up gear, deliver much flow of oil by all together. The system and the pumps have been studied for the practical wave energy conversion with the Pendulor. This system shall be able to develop a large Pendulor in the future for peaceful world. (Three Patents Pending)

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 (ripple); 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 way 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 as travelling through such a long distance. Therefore, utilization of the wave energy; -applied with the antenna principle, it can be done without difficulties. (Muroran I.T. 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. FIGURE 1⁽⁵⁾⁽⁶⁾ is the first floating type Pendulor which has been studied in Korea after Muroran I.T. closed the study in 2000. This device has applied new ideas; (1) Floater to be stable by active damping with the wave forces, (2) Optimization control of wave energy conversion, (3) Giant Rotary vane pump direct coupled with the pendulum, (4) Oil seal fits to the large pump. Japan created the ideas and Korea challenged developing of the plant by applying the technologies⁽⁷⁾.

WAVE POWER DENSITY IN THE WORLD

FIGURE 2 shows the wave energy distribution in the world, 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 (= 40kW/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



FIGURE 1 Floating Pendulum 300kW, Refined by, KRISO & YOOWON, Korea,⁽⁷⁾ (original one Jap. Patent, 4448972, 2003)⁽⁵⁾



FIGURE 2 Wave power distribution in the world with the unit kW/m, (US Dept. of ENERGY)

frequently attacks Japan lands with over 10 times stronger power. The Pendulum must survive towards them to accept not such the strongest machine but a clever and inexpensive one. The machine lets the dangerous waves go back to the sea as it does no energy conversion.

WAVE POWER FOR LARGE PENDULOR

Considering the magnitude of the wave energy potential on the EARTH, we must pay attention on the big energy converter driven by high energy density waves. Here introduces a study on the waves which 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 (in FIGURE 3)⁽⁹⁾. The authors tried

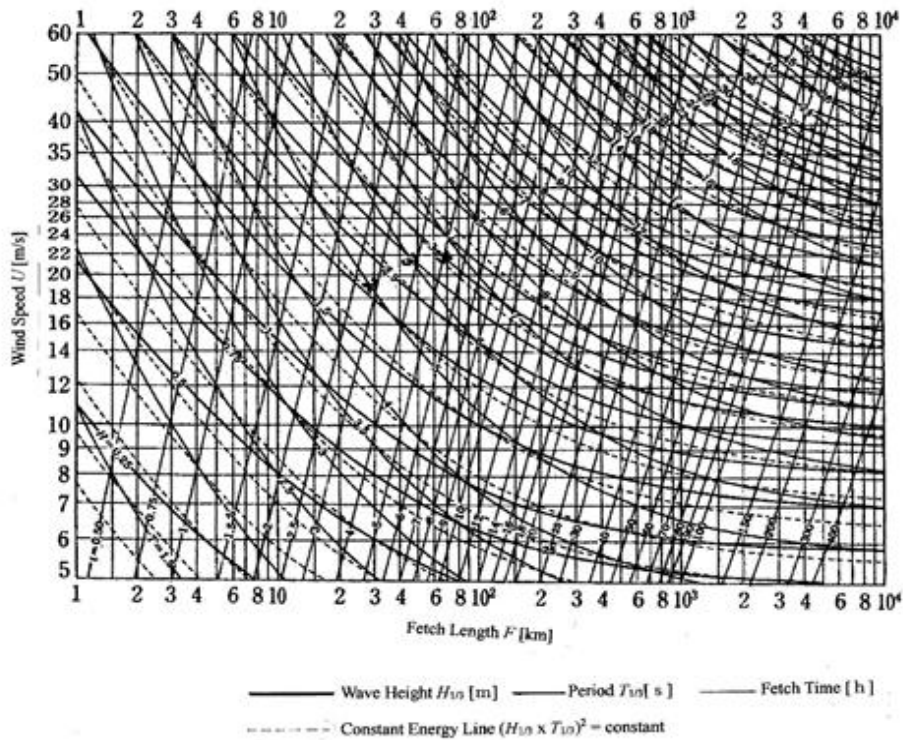
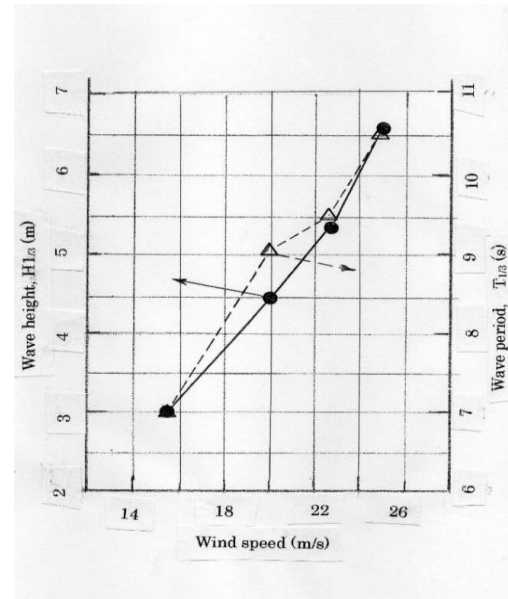
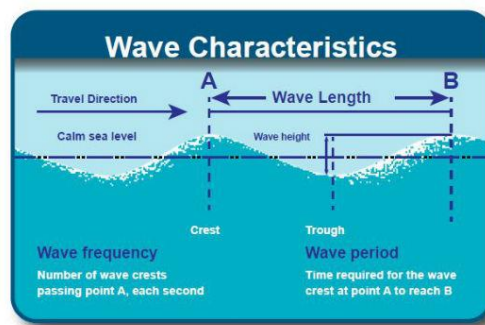


FIGURE 3 Wind-Wave forecasting curves, of Deep water,

TABLE 1 The Wind-Waves grown by Several wind speeds

Case No.	1	2	3	4
Terms				
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

**FIGURE 4** Period change by growth of Wave**FIGURE 5** Wave Characteristics(9) Relationship between blowing wind on the sea and growing waves

some investigations to find preferable waves which are good for driving the large Pendulum. **FIGURE 3 and 4** show the wave height: $H_{1/3}$ (m) and its period: $T_{1/3}$ at given wind speed (m/s), blowing duration (hour) and distance (Fetch length, km). In case of 10 hour wind blow with several wind speed, growing wave height estimated are shown in **FIGURE 4 & 5**. 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 speed wind. It means the wave motion changes slower as the blowing wind to be stronger. Therefore, when a large Pendulum is driven by energy rich waves, the richer the energy density, the operation condition of the Pendulum becomes the slower speed and the higher torque operation. This result tells us an important direction 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 attack to this study with new ideas: shown below. *[New Ideas for the large Pendulum: (1) Survival to the Storm by no-stopper $\pm 360^\circ$ free rotation, (2) Invention of, Hybrid H.S.T. for Generator driving, & (3) piston pump can work at the condition, well]*

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 becomes often offers a damage situation to the system. During sea operation of a Pendulum, we experienced three times of accidental breaking of the flapper legs by

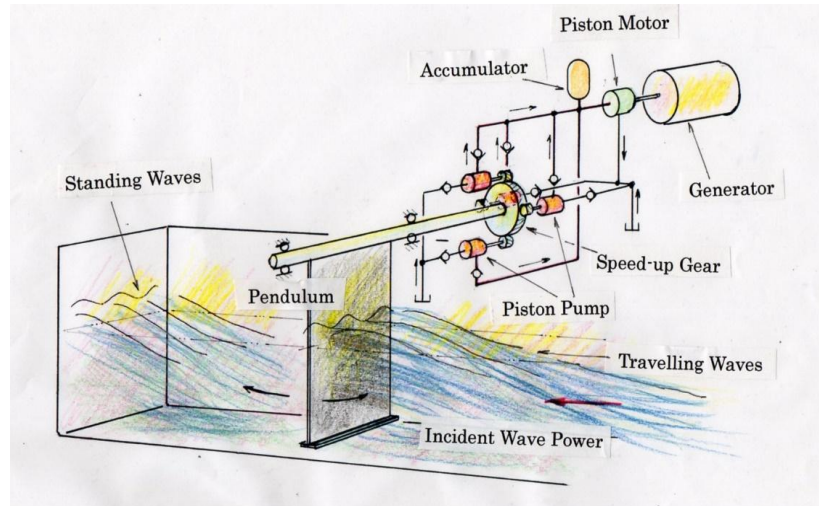


FIGURE 6 Principle of the Pendulum combined with the Hybrid H.S.T. (Patent app. 2017-015068)

impingement between the stopper and the legs.⁽¹⁰⁾ The happening gives us a hint to avoid the trouble;- by not to improve the legs stronger but to change the condition safer;- by no use of the stopper. We selected the Hybrid H.S.T. system for the Pendulum which requires no stopper as shown in FIGURE 6.⁽¹¹⁾

In FIGURE 6, a single pendulum drives four sets of geared piston pumps of the H.S.T. 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 to the value shown in EQUATION (1).

$$D_p = D_o \times (\text{divided power ratio}) \times n_p/n_g \dots (1)$$

Here, 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: $n_p = 7$ and teeth number of the gear: $n_g = 70$, D_p takes the value shown by EQUATION (2), that is the case of FIGURE 6.

$$D_p = D_o \cdot 1/4 \times 7/70 = 0.025 D_o \dots (2)$$

This result means that the system of FIGURE 6 can reduce the pump capacity required drastically, comparing with the former system of one set pump. The Hybrid HST of Fig. 6 has no stopper because of the system permits over 360° rotation of the pendulum in either direction. The pendulum motion amplitude: θ_a is shown by Equation (3) as a function of the incident wave height: H .⁽¹⁾

$$\theta_a = \frac{k_0 Z_0}{4Y_0 \sinh k_0 h} \times \frac{H}{2} \dots (3), \quad Z_0 = \sinh 2k_0 h + 2k_0 h \dots (4), \quad Y_0 = k_0 l \sinh k_0 h + \cosh k_0 h - 1 \dots (5)$$

here, 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 FIGURE 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 a tiny moment of inertia. The pump can be inherently to fit to the reciprocal rotation as well.

IMPROVEMENT OF THE SURVIVABILITY OF THE PENDULOR

The cause of damage on the wave energy converter observed was by shock loads most, not only on the Pendulum but also the Pelamis⁽¹¹⁾ FIGURE 7 and, the Oyster⁽¹²⁾ FIGURE 8. The shock load happened both places with the stoppers and the mechanical power- transmission where small gap existed between the parts faced with two of them which cannot become within a one part. The gaps make shock by impingement. In the case of impingement at the stopper, there likely concerns with big energy on it. Therefore, some components of the stopper are damaged. For instance, the tightening bolts of the stopper to be loosened at beginning then the all bolts were broken away to the final stage. The incident lets us make the mind, to improve the power take off



FIGURE 7 W.E. converter Pelamis UK

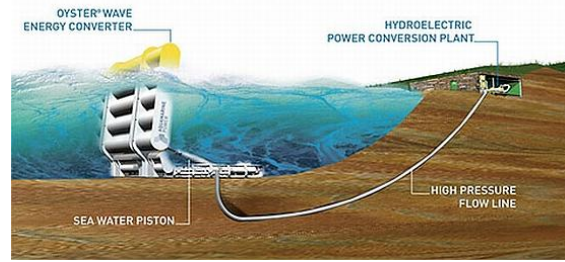


FIGURE 8 W.E. converter Oyster UK

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 HST developed shown in (FIGURE 6).

DESIGN OF THE HYBRID H.S.T.

FIGURE 9 is a trial design with 16 pumps to make a set of geared pumps for the Hybrid HST. This idea is for a MW class study on the large Pendulor. With 16 pumps and given the speed ratio: $z_1/z_2 = (120/9 = 13.33)$. It seems one of the balanced features from the engineering and the economic stand point. The case shown in FIGURE. 9, the pump speed is increased in 13.33 times higher than the case of no gear driving, 16 pumps of the displacement D_p , is shown by Equation (6).

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

Therefore, the case of Fig. 9, the 16 pumps have the 320 times small displacement each is enough for the pumps of the hybrid HST. Despite of such as 16 pumps drive even in parallel, each the load is divided into each the pump exactly by an error absorption effect to the teeth pitch error of the pumps. For design on the 7 teeth pinion of the Hybrid HST, which have no under cutting by the interference on the pinion of 7 teeth. That is an allowable limit condition with the sharpened teeth tips.

For the gear lubrication of the high tooth load/ slow speed operation, attentions written below are useful. (1) The teeth are hardened by nitriding process, polished by lapping to make $0.5 \mu\text{m}$ flatness. The error of tooth profile and pitch are not important in case of slow rotation (under 100rpm). (2) For the teeth strength, especially to contact pressure, we should pay attention carefully (oil film thickness at the contact point etc.). (3) For the gear design, the contact point to be pure rolling as perfect as possible. This kind of care makes steady lubrication by Elasto-Hydro-Dynamic Lubrication (EHL). This Hybrid H.S.T. idea can be used also for wind turbine. Because the system drives high speed generator with very slow speed turbine.⁽¹¹⁾

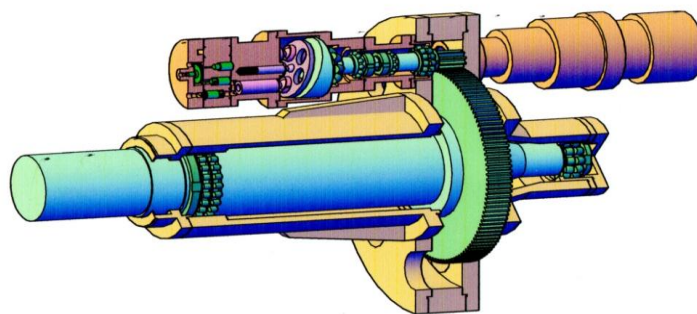


FIGURE 9 Geared Piston Pump set for Hybrid H.S.T. for 1MW Conversion
(Japanese Patent App. No. 2014-173194, 2014, T-Wave)

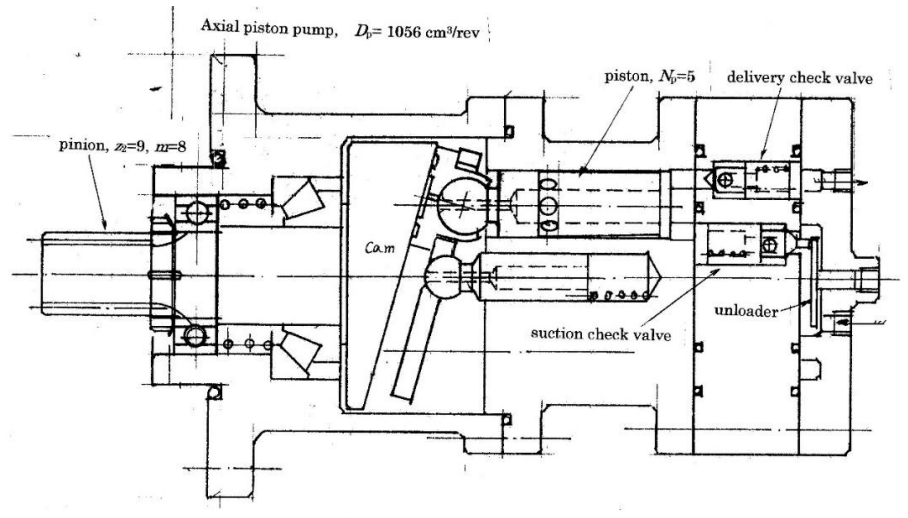


FIGURE 10 FIGURE 10 Piston Pump for Hybrid H.S.T

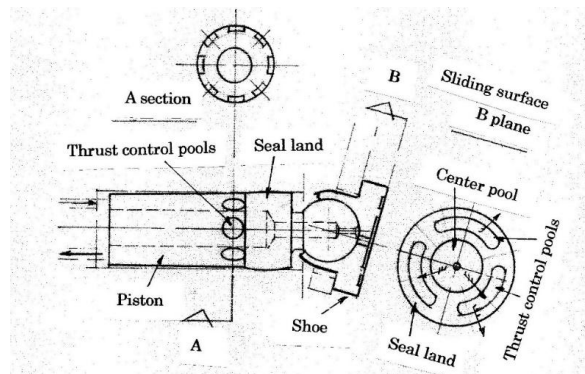


FIGURE 11 Piston and Shoe with self-balancer (Patent Pending)

PISTON PUMP

FIGURE 10 is the pump designed for the Hybrid HST for study purpose of the large Pendulor. It belongs to non-rotating axial piston pump group having 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 FIGURE 9 is the Hybrid pump for it,) ⁽¹²⁾ the displacement D_p required for the hybrid piston pump is shown by the equation (6)

STUDY ON THE PISTON AND THE SHOE

The large Pendulor has an energy loss problem because of the HST which is oil leak at the slow speed operation. Axial piston machine uses swash plate to convert reciprocal motion to rotary motion. A conventional hydro-static bearing has been used for the swash plate. This component does make the efficiency drop of the HST. The author experienced an observation of the swash plate 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. FIGURE 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 FIGURE 11. On the surface of the static bearings (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. FIGURE 11 shows that the piston clearance is controlled to move the piston center, Therefore, when the pressure is bigger, the lateral force becomes the bigger. The principle: (1) The piston configurations are located right to left; ball formed joint, clown formed seal, pools located on the taper formed guide. The piston can rotate within the lateral gap by the tapered guide which affects pressure change of the pools. (2) When a normal vector pushes the shoe at the sliding center shown in FIGURE 11, one force vector component of up direction, drives the piston by anti-clock wise moment. Therefore, on the taper part of piston, upper side clearance becomes larger and lower side one becomes minimum. (3) 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)

CONCLUSIONS

The idea of Pendulor with Hybrid HST can be concluded as below. (1) The new idea has been shown here that the Pendulor can be survival against the storm. It is realized by applying with Hybrid HST assembled into the Pendulor system. (2) This idea contributes to the conversion system not only being survival in the storm but also open a new possibility to develop MW class large Pendulor by Elasto-hydrodynamic lubrication (EHL) technology for the high torque and slow speed operation. (3) The axial piston pump of small moment of inertia, can improve the Pendulor efficiency at high torque low speed operation. This idea on the Hybrid HST is suitable for the large wind turbine application, too. (4) The converter on Moving Body type, "Pelamis and Oyster", the cause of failure was studied to overcome the problems in the future.

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