

Study on Pendulor Wave Power Converter for Coastal Operation of Sri Lanka

– Design of the Piston Pump for the HST (Hydro-Static Transmission) of the Pendulor –

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Abstract

Pendulor is a moving body type Wave Power Converter. It can do an efficient power conversion though; its survivability hasn't been enough in the stormy sea operation. The authors invented a new Pendulor which can treat the shock load safely by different way at the storm. The new Pendulor uses a hybrid piston pump as a component of the HST (Hydro-Static Transmission) for the conversion. This study is a case of 50kW Pendulor for Sri Lanka Coastal use. Since the cause of the trouble, begins from action of the restrictor which keeps the Pendulum stroke within a limit at the emergency. It is a stopper of huge moving mass. The new idea of exchanging the pump from a reciprocal type to a rotary type one, it also suggested a new technology. By the hint, we invented the hybrid piston pump. After that, the Pendulor is able to get the free stroke motion with the simpler system of the pendulum. The system also brought the sockless conversion toward the stormy condition. It can, not only contribute to the greater survivability, but also save cost of the electricity generated.

Key words: Pendulor, survivability, hybrid piston pump, slow speed high torque operation, E.H.L. lubrication, speed up gear.

1. Introduction

The Pendulor device, it belongs to the moving body type conversion which is based on resonation and impedance match operation for the efficient power conversion⁽¹⁾. One of the problems is insufficient of the survivability against the storms. For this situation, we invented another Pendulor which is definitely safe by taking away the weak parts of the Pendulor by exchanging the motion style of the pump, from reciprocal motion to a rotary motion⁽²⁾. Since the new Pendulor doesn't use the stopper, there is no shock caused by the stopper. Therefore, the new wave power conversion can do no shock operation. The survivability shall be improved by applied with the piston pump invented for this purpose (Japanese Patent pending). We studied the pump as a Hybrid one suited to the Pendulor first, then the pump should work on the slow speed and high torque condition of more severe lubrication. In order to overcome the condition, we tried on the two new ideas on the pump parts; they are a piston and a shoe. A case of swash plate type axial piston pump designed for the HST of the 50kW Pendulor model of Sri Lanka Coast use was reported.

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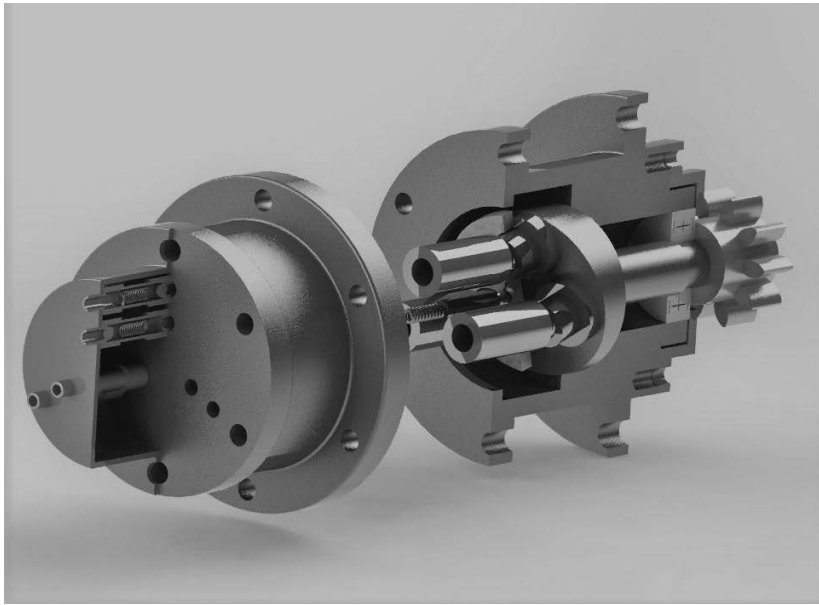


Fig. 1 Axial piston pump designed for the hybrid HST system of Sri Lanka Coast Use

Since the pump of Fig. 1 is non rotating type, the cylinder block doesn't rotate but the disc only, so that the moment of inertia takes very small value. It affects well to the conversion system to affect resonant frequency change little because of small of the pump inertia. The pump seems very simple and robust, too⁽³⁾.

Table 1 shows the merit of the axial piston pump (shown in Fig. 1~2), applied into the conversion system. The comparison between the two types of the pumps (1) Swash plate type and (2) Bent axis type, it shows the deference clearly. Bent axis motor is used widely for winch driving, especially for need of soft starting of the winch when it is loaded in hanging position.

Table 1. Comparison of the Axial piston motor, (1) Swash plate type and (2) Bent axis type one

Motor	(1) Swash plate type, (Refer Fig. 1)	(2) Bent axis type (Refer Fig. 2)
Motor construction	Simple & Smaller	Complicated & Bigger
Motor body size	Small & light	Big & Heavy
Characteristics of the motor	Excellent	Excellent
Survivability	Good	Good
Motor price	Inexpensive	Expensive
Moment of inertia	Small by disc cam only	Large by cylinder block assembly

When we use axial piston machine for winch driving, as an example, moving parts of the piston and the shoe are the most important for skillful operation for big goods treatment. At that condition, sliding parts are not able to be lubricated well because of the condition must be fur beyond from the critical point for

easy sliding. Therefore, the piston and the shoe should start from a severe metal contact state. It would begin a typical stick slip Vibration. Here we discuss the technology to solve this type problem.

The ocean wave energy conversion with HST has been also facing to such problem like as the slow speed and heavy load driving. Of course, the system must work safely without vibration.

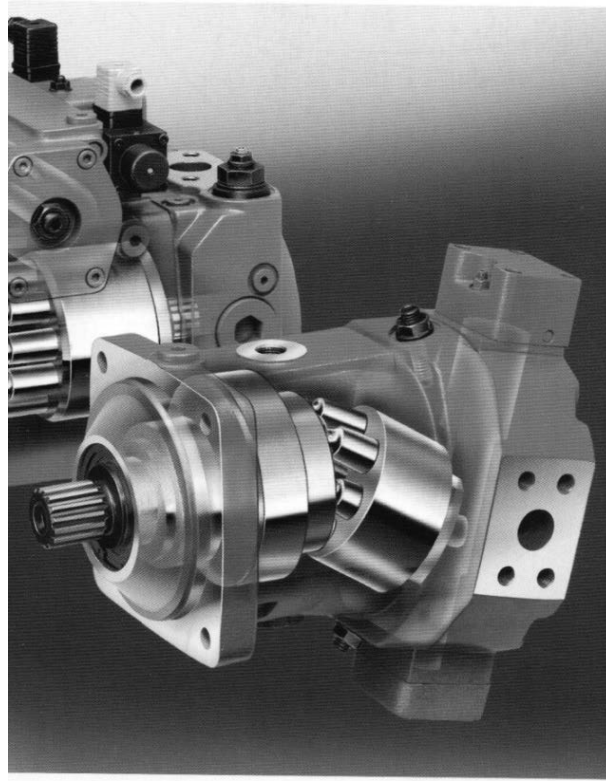


Fig. 2 Axial Piston Pump/Motor of Bent Axis type (Front one, Bosch Rexroth)⁽⁴⁾

2. Hybrid Axial piston pump

First of all, this study started from changing the lubrication better towards back to normal for protect the sliding parts with sufficient lubricant film. In order to realize it, the pump of the HST is driven by the Hybrid drive system shown in Fig. 3 (Patent pending). The system can drive the pump under a much smaller torque and faster speed condition with a new Hybrid driving mechanism explained in Table 2.

The system of Fig. 3 uses a round disc formed gear for speed up one. Therefore, it shall be simplest one to be multi-purpose application of (1) speed up and (2) power dividing as long as it avoid the interference problem by taking gear design with shift gear method and helical form teeth combination. It can take the speed ratio = 10 by one step, without difficulty. If we try arc of circle teeth for this purpose, the possibility shall be increased than more by involute teeth gear only. This form could be applied for the future subject of a MW class Pendulor.

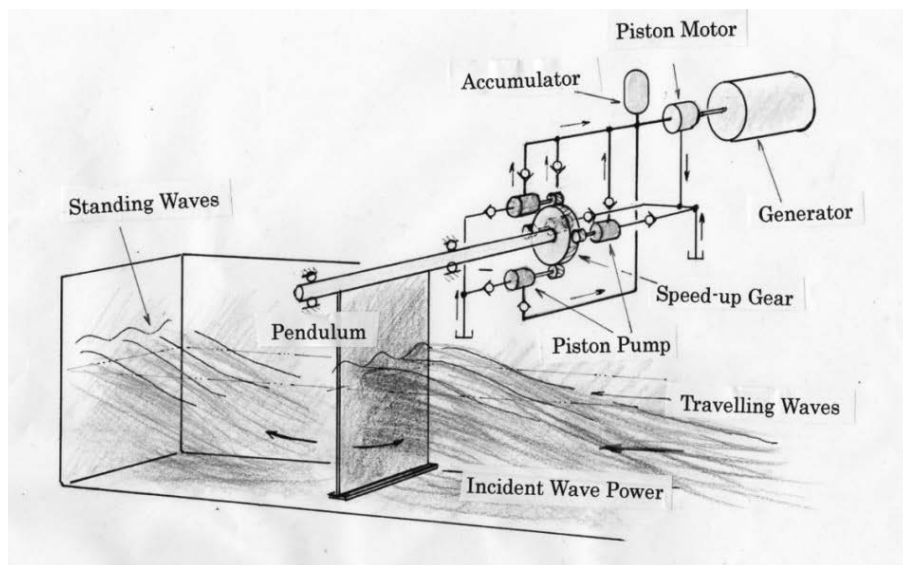


Fig. 3 Hybrid Axial Piston Pump Drive System (Japanese Patent Publication JP 2016-37956)⁽⁵⁾

Table 2 summarized the driving principle of the Hybrid Axial Piston Pump System.

Since the ocean wave motion belongs to huge power and ultra slow speed moving phenomenon, therefore, conversion of it for driving generator has been a basic mismatch subject of the engineering. This Hybrid piston pump driving system was borne to change the miss-match condition to be remade better with the fundamental consideration for the wave power utilization being friendly to the human society..

The Principle of this pump driving is changed better at three main parts;-

- (1) Making weaker the driving force of the pumping of the HST.
 - 1.1 Every the driving points of the power divided, must be meshed with the individual gear.
 - 1.2 Both of Dividing power & Increasing speed, produce a big work done using very small pumps
 - 1.3 Use of small pump in high speed operation, improves lubrication and reliability much better.

Table 2 Driving Principle of the Hybrid Axial Piston Pump System (Refer Fig. 2~3)

(1)	Purpose: Development of a strong & efficient wave power converter being survival against storms.
(2)	Action for (1): Making the lubrication better with much thicker oil film by reducing load under Higher sliding speed.
(3)	To change better, by induce the Hybrid driving system. The <u>problem of heavy load + slow speed,</u> change to <u>lighter load + swifter speed condition</u> covering with thick oil film.
(4)	Principle: Producing the merits by (A) <u>dividing the drive power into 4 points or more with a speed up gear,</u> (B) <u>Generator driving by HST can use much smaller pump which has little Displacement .(1/ number of dividing point, x value of speed up ratio).</u>
(C)	For example, in case of 10= dividing points with 10= speed up ratio, <u>Displacement required as the pump for the HST = [1/100]= (1%) of the standard single system.</u>

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- (1) Pendulum is one of the moving body type wave energy converters applied with antenna principle to generate electricity from the ocean wave motion. Despite of the wave motion doesn't work quickly itself, but its ultra-high pressure can make rapid oil flow with no problems. A big pendulum can convert a high-speed rotation by the motion of it to drive the generator exactly.
- (2) The difficulty of the Ocean wave energy conversion is Development of a converter of acceptable low costed electricity which can be cheaper than the cost by the Atomic Plant can do. This idea of the new Pendulum has been born for not only to clear the cost target but also improve the survivability towards the storms. The idea is no stopper system which allows the Pendulum's motion free.
- (3) For realizing of this idea, the new Pendulum adopted a hybrid H.S.T. for generator driving that is very important. The exchange of the power line has brought a possibility of increasing the conversion capacity drastically. Therefore, we should study this idea for the future ocean wave energy utilization hoping the world to be better.

(1) Pressure: $p = 20$ MPa, (2) Displacement: $D_p = 50$ cm³/revolution, (3) Piston, 3 pistons, Dia. = ϕ 36, (4) Inclined disc cam, inclined angle $\alpha = 14^\circ$

(1) Speed up ratio: $z_2/z_1 = 100/10$, (2) Pressure angle: $\alpha = 20^\circ$, (3) shift value: pinion $x = 0.5$, (4) shift value: gear: $x = -0.5$, (5) helical angle: $\beta = 20^\circ$ (pinion : clock wise twist and gear: anti-clock wise twist direction)

General Explanation on this Hybrid HST system

The capacity of the piston pump is prepared with a little bit enough level. The reason is if we take normal size for the indoor test, 1/10 scale device shall become to 1/1000 level power capacity. The level seems too small for taking reference data to develop the full-scale device.

In the case of with $D_p = 50 \text{ cm}^3/\text{revolution}$, for the HST of the indoor test, round 1 kW electric power generation test would be possible in the laboratory.

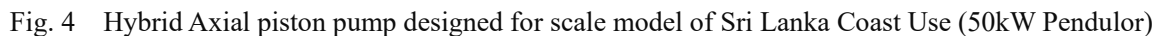


Fig. 4 is the Hybrid axial piston pump, of 50kW model. A case of Coastal use of Sri Lanka. It shall be made and tested by University of Peradeniya of the University's Machine shop and 2-Dimensional Wave Tank for the Scale model Pendulum test is located in the Campus.

Table 3 Specification of the Pump (Non Rotational type shown in Fig. 4)

	(1). Displacement $D_p = 50 \text{ cm}^3/\text{revolution}$. (2). Number of pistons $N_p = 3$, (3). Piston diameter = 36 mm, (4). Disc Cam being inclined angle = 14° , (5). Delivery pressure $p = 20 \text{ M Pa}$.
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3 . Control of the shoe sliding friction and the restoring moment of the shoe (Refer Fig. 5)

Fig. 5 is the Principle to control the Pump operation optimal by the control of the shoe friction to be small and stable for better Wave Power Conversion in Slow Speed and Big Power Field

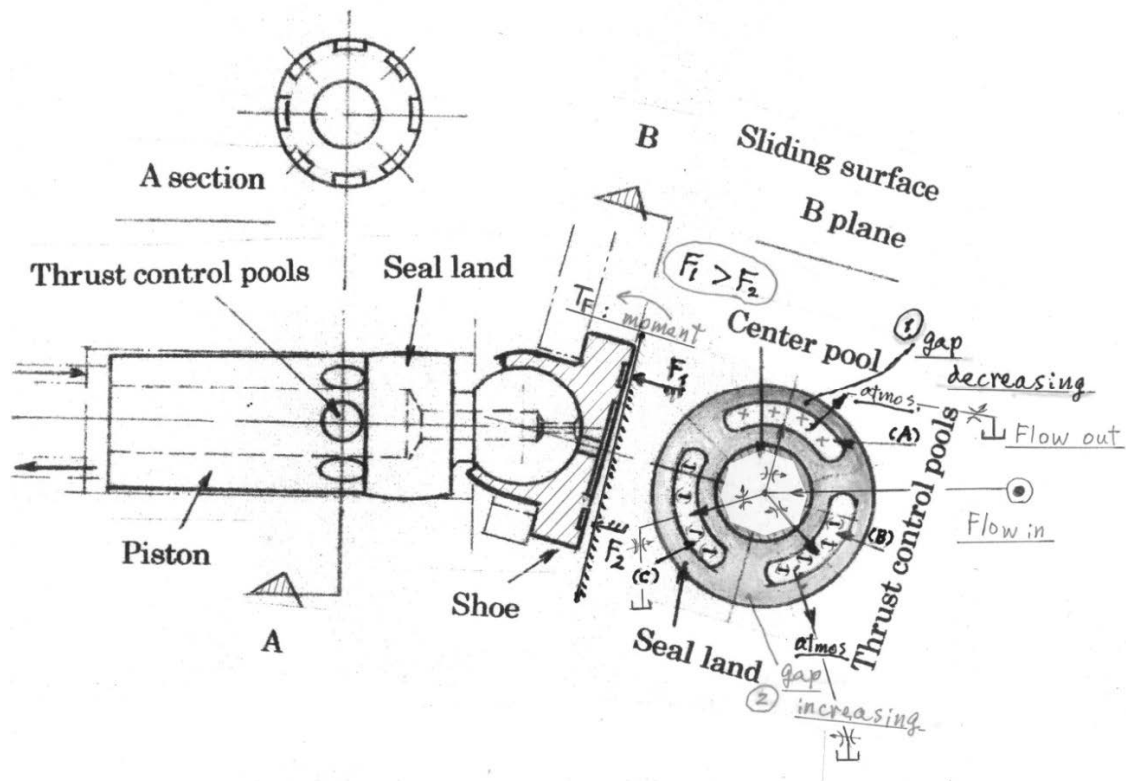


Fig. 5 Piston & Shoe Assembly of Self Balance Design for the HST of Sri Lanka Coast Use (Japanese Patent Pending: Pat. Application No. 2017-108656)⁽⁶⁾

On the surface of the shoe (Fig. 5), there are 3 sets of the same units; of the static bearings for producing a balanced bearing task totally. They are placed around on the center of the shoe circle symmetrically. From the center to outer circle, (1) center pool, (2) seal lands of flow-in, (3) thrust control pools and (4) seal lands of flow-out, are located. The three units which support the pushing load by the action of the pump piston transferred to the three hydro-static bearing pads, on the sliding surface.

The shoe surface keeps parallel position to the swash plate, in standard, but sometimes it deviate from the

position, this shoe structure makes pressure change by the deviation. For Example, Fig. 5 shows a condition of the shoe takes a tilted position when at (A) pool increases the oil pressure and at (B)~(C) pool decrease the pressure because of the flow-in and the flow-out combination are different by the pool location. There is a relationship between the tilt and pressure change of the control pool location. This pressure change appears with an affect into the shoe tilting back the shoe to be parallel with the swash plate again. The shoe tilting is done by pressure drop in Fig. 6 appears with pressure drop by the Equation (1).

The pressure of the thrust control pool of (A)~(C) is the function of real flow-in value to the three control pools. Since the real flow-in is difference between actual flow in and actual flow-out, deviation of the shoe surface from the parallel position must make actual flow change which can be possible at the flow change of which leads the condition to recover the parallel position again.

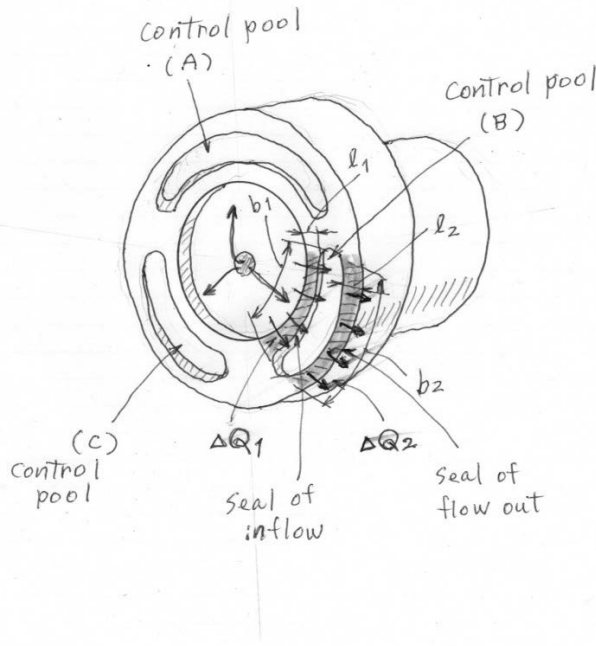


Fig. 6 Oil flow of the shoe sliding surface with pressure drop

$$\Delta Q_1 = (b_1 h_1^3 / 12 \mu l_1) \Delta p_1 \dots \quad (1)$$

Here, ΔQ_1 : oil flow of the seal land of inflow side, b_1 : seal width of inflow side, h_1 : gap of the seal inflow side, μ : viscosity of the lubricant, l_1 : seal width of inflow measured to the right angle direction of the b_1 and Δp_1 : pressure drop at the seal of inflow side.

The same relationship between flow and pressure drop on the seal of flow out side written in the Equation (2).

$$\Delta Q_2 = (b_2 h_2^3 / 12 \mu l_2) \Delta p_2 \dots \quad (2)$$

The flow path ΔQ_1 and ΔQ_2 are connected in series, the value of them takes in a same level.

$$\Delta Q_1 = \Delta Q_2 \quad \dots \quad (3)$$

Since the pressure drop is the function of the oil flow through the seal land, we can foresee the oil pressure of the control pools. Therefore, we can make a piston shoe which keeps the non metal contact condition applying with the design shown in Fig. 5 and 6. The authors have been trying the numerical simulation of them.

4. Conclusion

The Idea to Improve the Ocean Wave Power Converter Pendulor, has been reported. The study is at a beginning stage, though, it can be concluded as written below.

- (1) The Pendulor belongs to the moving body type converter which has a problem on insufficient Survivability towards storm. This study is for the new Pendulor to overcome it with the Hybrid HST which brings a free movement of the moving body. It expects to the Device to let it go into shock-less operation.
- (2) The pump to fit to the purpose well is, of non rotational type, which must overcome slow speed operation under a high torque load. The idea of hybrid operation with speed up and self optimizer control to the shoe lubrication can realize minimum sliding friction. The research group has been studying the numerical investigation of the shoe design.
- (3) University Peradeniya Sri Lanka has been preparing the new Pendulor 50kW scale model pliers for the Sea test.

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