AUTONOMOUS OPTIMIZATION CONTROL AND THE CONTROLLER FOR PENDULOR (AN OCEAN WAVE POWER CONVERTER)

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ABSTRACT

A wave power converter: Pendulor, works with 40% efficiency at an optimal condition. Irrespective of change the wave climate, an Autonomous Optimization Control (AOC) adjusts hydrostatic power transmission to keep the Pendulor in the best match with the waves. This is a new system to know the wave climate from the Pendulor motion. AOC improves the system reliability and solves load sharing problem in the HST lines.

KEY WORDS

HST, control, wave power, autonomous, efficiency, Pendulor

INTRODUCTION

In order to reduce the ocean wave energy cost, it has been studied on an autonomous control of the Pendulor, which was equipped with a hydrostatic power transmission (HST). Since the Pendulor [1] absorbs energy best when it resonates with the waves under an impedance match condition, an Autonomous Optimization Controller (AOC) works to keep the best condition irrespective with the sea climate. The controller knows the wave climate from the pendular motion and keeps the conversion condition optimal as

adjusting damping parameters. The Pendulor becomes to be simple and competitive because it does not need a conventional wave sensor (very expensive) in its system. There includes other ideas to improve the utilization of the wave energy. In order to make the system practical, analogue hydraulic processor was invented to control a variable motor, which is governed by the analogue signal. The studies are reported here.

PENDULOR AND ITS OPTIMIZATION

Fig. 1 shows a wave power converter named Pendulor.

In order to get steady output, the system is so designed as shown in **Fig. 2**. The pendulum drives a rotary vane pump, which supplies oil towards two motors by turns. Even though each the motor torque shows wavy variation, superposing the two cancels the variation by phase lag π between the two. When the accumulators of the lines have proper capacity, conversion efficiency goes up to the peak. Therefore, it converts wave power very well besides improving the output steady [3].

The diagram illustrates a hydraulic model for a tidal turbine. The upper portion is an electrical circuit diagram. It features a central generator (G) connected to a battery (BATTERY) and several switches and meters. The lower portion shows a physical model of the turbine in a water chamber. The turbine is mounted on a vertical axis and is connected to the generator. Dimensions are indicated: L is the length of the turbine, H is the height of the water chamber, and h is the height of the turbine. A sinusoidal wave is shown next to the turbine, representing the tidal flow. The wavelength of the wave is labeled λ . The water chamber is labeled 'water chamber' and the caisson is labeled 'caisson'.

When the natural frequency of the pendulum in water coincides with the frequency of the peak power spectrum, the pendulum resonates to the waves most. In the resonant state, and when the generator load is in

Natural waves change the wave height day by day so that it is necessary to adjust the Pendulor to fit to the waves to keep the conversion optimal. AOC controller does it in a way explained here after.

Fig. 3-a & 3-b show examples of the wave climates. It is seen in Fig. 3-a, a good relationship between the wave period and the wave height in a statistic viewpoint. From

Fig. 3-b, wave power, (which is function of the wave height and the period) can be calculated, by only knowing the wave height or period. The relationships are

shown in the Eq. (1-2). By the AOC system shown in Fig. 4, the wave power characteristics can be known indirectly as long as the location is determined.

Figure 4 Principle of the AOC controller

$$H_{1/3} \approx 0.0387 T_{1/3}^{2.2} \quad (1)$$

$$\bar{W} \approx 5.85 \times 10^{-3} T_{1/3}^{4.2} \quad (2)$$

here, $H_{1/3}$: significant wave height, $T_{1/3}$: significant wave period.

Since the wave power $\bar{W}$ is function of the wave period $T_{1/3}$ in statistics, Pendulum, which drives a generator in synchronous speed, can keep the optimal condition when the displacement of the motors is controlled in the value shown in the Eq. (3).

$$T_{1/3}^{2.4} \approx 1.13 \times 10^3 \left(\frac{D_m n_m}{r A_p \eta_{vm}} \right)^{1.2} \quad (3)$$

here, D_m : displacement of the motor, n_m : motor speed (rev./s), r : arm radius (Fig.4), A_p : piston area of the cylinder (Fig. 4), η_{vm} : volumetric efficiency of the motor. However, the motion amplitude of the pendulum; - that means the delivery flow of the pump-, is function of the wave power during the Pendulum operates optimal. As the result, the displacement D_m should be adjusted as function of pressure $\bar{p}$ shown in Eq. (4) of the motors to keep the condition.

$$\bar{p} \approx 3.18 \times 10^6 \frac{\eta_1 \eta_p (D_m n_m)^{1.2}}{\eta_{vm}^{1.2} (r A_p)^{2.2}} \quad (4)$$

here, η_1 : power conversion ratio by the pendulum.

The AOC system adjusts D_m following $\bar{p}$ to keep the relationship of the Eq. (4). Since $\bar{p}$ is the power line pressure, it is very simple to use it as the signal to control the motors [4]. The matter is how to know the average value of the pressure around 30~60 sec. in a practical way. The authors studied a circuit combined with an accumulator and a choke for it.

System and the components

The motor governed by the AOC controller, uses oil pressure as the control signal for adjusting the displacement. One of them is A6V series motor of Mannesmann Rexroth made [5]. The AOC controller sends pressure signal to the motor. The controller is an analogue processor, which consists of a pressure regulating valve (PRV) and a damper. Fig. 5 shows the principle. The PRV generates control signal p_c from $\bar{p}$ to adjust D_m governed by the Eq. (4). The damper acts to find an average value of p i.e. $\bar{p}$. Pressure p pushes a spring via a piston and the displacement of the piston x is converted to the signal p_c . Since the damper is attached

with the piston, the displacement x is nearly proportional to $\bar{p}$. Force balance of the piston is written in the Eq. (5) when the resistor is linear type.

Figure 5 The AOC controller

$$\frac{c_3 a_d^2}{k_s} \ddot{x} + \dot{x} + x = (F_{so} - a_p) / k_s \quad (5)$$

$$\text{here, } c_3 = \Delta p / q_3 \quad (6)$$

a_d : damper piston area, k_s : spring constant, F_{so} : initial force of the spring, a_p : piston area, Δp : pressure difference, q_3 : flow to pass through the resistor. From the Eq. (6), time constant T_x of the displacement x is derived and it is shown in the Eq. (7).

$$T_x = \frac{c_3 a_d^2}{k_s} \quad (7)$$

Since the range of the wave period is from 5 to 15 second, the AOC must not be influenced the period directly. For example, the AOC shown in Fig. 5 has a very large time constant; $T_x = (25 \sim 100)s$.

Numerical simulation

Fig. 6 shows a block diagram of the Pendulum combined with the AOC controller. It consists of (1) pendulum division, which delivers oil, (2) accumulator division, which determines the pressure change and (3) motor division of which displacement is governed by the AOC controller. The pressure feeds back against the wave force and it makes the line pressure stable. But the balancing level likely deviates from the optimal one without the AOC control, because, the pressure feed back is not enough and its effect is limited by the system configuration.

Figure 6 Block diagram of the AOC controller

Fig. 7 shows typical simulation results of light, medium and full load operation. It supposed that leak loss in the No.1 line worn down was 5 times greater than the one in the No.2 line normal. All the cases, line pressure started from 4.0 MPa when incident wave power stepped to 1/4, 2/4 and 4/4 range up.

Figure 7 Simulated result controlled by AOC controller

Pressure p_1 (No.1 line) and p_2 (No.2 line), which oscillate wavy, shift their average levels for getting the new balancing conditions. Nevertheless the No.1 line had an abnormal leak loss, p_1 was kept within 84~88% of p_2 . The results were given by AOC controller to increase the displacement D_m of No.2 motor, which could carry more load in lower pressure operation. On the contrary, AOC controller adjusted to be smaller the displacement D_m of No.1 motor to pass fewer flow in the No.1 line

Figure 8 Simulated result without AOC controller

Fig. 8 shows a simulation result without the AOC control under the same operation of Fig. 7. Both the pressure p_1 and p_2 continued increasing so that they reached to a dangerous zone especially p_2 was more serious. Since the pressure difference between p_1 and p_2 will be increased during a long time operation, load distribution of the motors shall become likely worsened. It causes the HST to be operated at a poor efficiency.

Comparison between the simulation and the sea test

Fig. 9 shows typical sea test result observed Muroran coastal site. Because of no AOC controller for Pendolor, there recorded a quite big pressure difference (1 vs. 2) between the lines nevertheless there was no significant parametric difference between them. The shape of the pressure is similar to the one of Fig. 7~8.

Figure 9 HST line pressure at sea operation

Since the pressure is function of the volume captured inside the accumulator, the volume difference can make an enlarged pressure difference after long term integration. It does while the Pendolor is working. Therefore, negligible small difference can make a large unbalance such as the one shown in Fig. 9. Comparing with Fig. 7 and 9, it can be seen that the AOC controller improves the condition.

CONSIDERATIONS

Time constant of the ocean wave climate is larger than a few hours though, it includes many wave groups, which last several minutes with higher wave power. In order to respond to the wave groups, the AOC controller should have a time constant to fit them. Leak flow from the

piston shall become comparable to the flow of the resistor so that it is the key point to reduce the leak and to stabilize the flow of the resistor. The resistor must be dust free. Fig. 5 shows a resistor to be popular for the purpose.

CONCLUSIONS

Through the study, it concluded as follows.

1. For an optimal wave power conversion, the HST selects a scheduled flow/pressure relationship, which gives Pendulor the impedance match condition. AOC controller makes it to adjust D_m by means of the line pressure. It can control a popular motor of the market.
2. AOC controller keeps the line pressure within a normal level and solves unbalanced load sharing problem between the two lines.
3. Considering a good responsibility and stability in parallel, determination of time constant is important. Fig. 7 was taken under $T_c=28.8s$.
4. The AOC controller is patent pending.

ACKNOWLEDGEMENT

Prof. H. Kondo, Muroran Inst. of Tech., was the head of the Pendulor project. The sea test was done by the team through several years. The pump for the HST was manufactured by Narasaki Co. and Nagasawa Co. Muroran. The Ministry of Education Japan and Cold Region Port and Harbor Institute Center supported the study.

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