Development of Passive Oil Compensated Shaft Seal Module for Kuroshio Turbine

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***Abstract*— The Kuroshio turbine is a submersible power generator designed to be working against Kuroshio Current with an exclusively long system maintenance period. The long-term operational reliability of the shaft seal is one of the key factors in designing the Kuroshio turbine. Inspired by the ROV oil compensation system for thruster bearings and electrical junction boxes, a passive oil compensated shaft seal module, which is integrated with an oil compensator and shaft seals, is developed for a Floating Kuroshio Turbine (FKT). The passive oil compensator balances the surrounding seawater and the oil pressure, the internal spring evenly maintains the oil pressure slightly higher than the surrounding seawater to prevent water ingress. The new design of the passive oil compensated shaft seal module features high reliability, maintenance free and adaptability to any water depths, which will benefit and prolong FKT working endurance significantly. This study introduces different types of shaft seal and the concept of passive oil compensated shaft seal module. Then, a 1:25 scaled experimental model is established for several pressure tests and its performance is demonstrated.**

***Keywords*— Shaft seal, hydraulic motor, pressure compensation, generator, ocean current energy**

I. Introduction

As environmental awareness rises, developing renewable energy to substitute traditional power generation like thermal or nuclear power becomes the consensus for the developed countries. Kuroshio, with characteristic of static current direction and velocity, might be the key development topic for power generation. Floating Kuroshio Turbine (FKT) is developed according to the flow patterns of Kuroshio Current east of Taiwan. The 1:5 scaled 20 kW FKT testing unit is planned to be anchored at a water depth of 50 m, while the floating power generating turbine is designed to be working continuously in the water depth between 20~30 m. The 1:1 scaled 0.5 MW commercial unit will be anchored at 250~500 m water depth and the working depth of the floating turbine is between 50~100 m. To reach the maximum generation efficiency, FKT is capable to change working depth and pitch by controlling water volume in the wing-shaped ballast water tank. As discussed above, FKT would face the challenges of pressure difference up to 11 bar and watertight capability especially at the rotating shaft seal. In order to prevent water ingress, building a reliable shaft seal module is an important topic.

Shaft seals are widely used in different fields. A mechanical seal is composed with a shaft rotating seal and a stationary seal. A spring is utilized to push the rotating seal against the stationary seal to achieve waterproof. Zhu and Wang developed a hydrostatic pressure mechanical seal to improve the efficiency of traditional mechanical seal [1]. A compensation slot is machined on the stationary seal which allows for external high pressurized gas entering, the shaft sealing efficiency of low rotating speed machines could be improved by modelling and simulating the pressurized gas between stationary and rotating seals. A Japanese company “Kobelco” modified the design of traditional vessel stern shaft seal by adding an active air pressure control unit and a gravity oil tank unit for the pressures compensation. The modified design not only enhance the sealing capability but also protect the ocean from oil spilling. To reduce seal ring wear from lateral and canting displacements, Ezekiel proposed a traditional active hydraulic compensation shaft seal [2]. A hydraulic pumping system equipped with a pressure regulating valve is used to compensate the pressure difference in both sides of a shaft seal between the internal oil and the external seawater. The design of suspended sleeve could also reduce wear on the shaft seal. Since an active hydraulic pumping system is added for pressure compensation, the concept is appropriate to be applied to the equipment that is placed under severe environmental pressure changes such as a submarine.

FKT will be deployed into water for a long-term power generation with very limited annual maintenance. Therefore, the reliability of the shaft seal is an important design factor of FKT. With a very limited internal space in FKT, is not suitable to install an active hydraulic pumping system and the power consumption of the hydraulic system will be another issue to be concerned. Therefore, a dedicated FKT passive oil compensated shaft seal module that is commonly found in the design of remotely operated vehicles (ROVs) is presented in this work. ROV hydraulic thrusters are mainly composed of a hydraulic motor and a bearing housing. The hydraulic motor is the main power source while the bearing in the housing is responsible to maintain shaft position and to reduce vibrations. Since the maximum operating depth of ROVs could be up to 6000 m, the bearing housing will be filled with oil and connected to an external oil compensator to balance the pressure differences between the internal oil and the external sea water as shown in Fig. 1. The oil compensator uses a

movable piston and a special rubber diaphragm to separate oil and water, the position of the piston varies with the working water depth to balance the oil and water pressure. Furthermore, the internal spring of the compensator provides an additional pressure to the oil, so the oil is squeezed out to the surrounding water firstly to prevent water ingress if leaking happened.

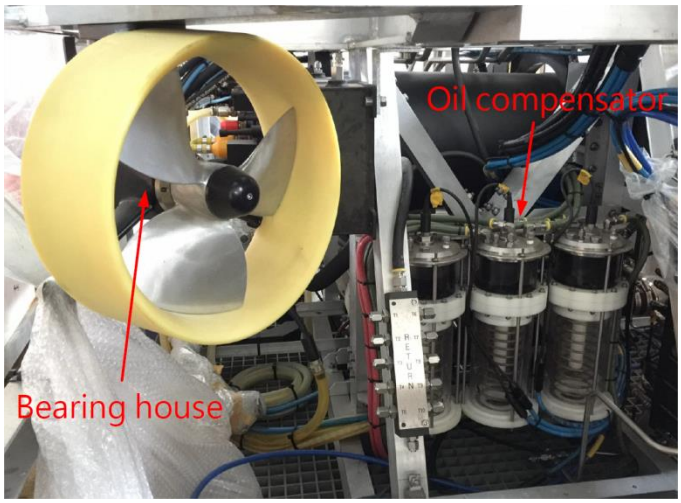

Fig. 1 ROV thruster assembly. ROV thruster uses an oil compensator to compensate the pressure between the bearing housing and the external water pressure to prevent pressure effect in different water depths.

FKT passive oil compensated shaft seal module consists of three main parts: passive oil compensator, shaft seal module and reservoir as shown in Fig. 2. The passive oil compensator is used to balance the internal and outer pressures, and the preload spring is installed to prevent water ingress. There are totally three shaft seals used in the shaft seal module and they are separated by two spacers. The shaft seal module is connected with the passive oil compensator to strengthen sealing capability. In addition, a tapered roller bearing is installed into the shaft seal, so the axial and radial loads can be reduced on the seals. A reservoir is used to collect the internal oil leaking if shaft seal encounters severe wear after long time operations. The proposed passive oil compensated shaft seal module for FKT is described in Section II. Section III describes testing result of the shaft seal up to 100-m water depth. The design, fabrication and pressure test of the shaft seal is for the 800 W (1:25 scaled) FTK Finally, Section IV presents conclusions.

II. Design of Passive Oil Compensated Shaft Seal Module

This section explains the design of passive oil compensated shaft seal module for 800 W FKT including the details of 440 c.c. passive oil compensator and shaft seal module. The operational concept of the integrated module shall also be mentioned.

A. Design of Passive Oil Compensator

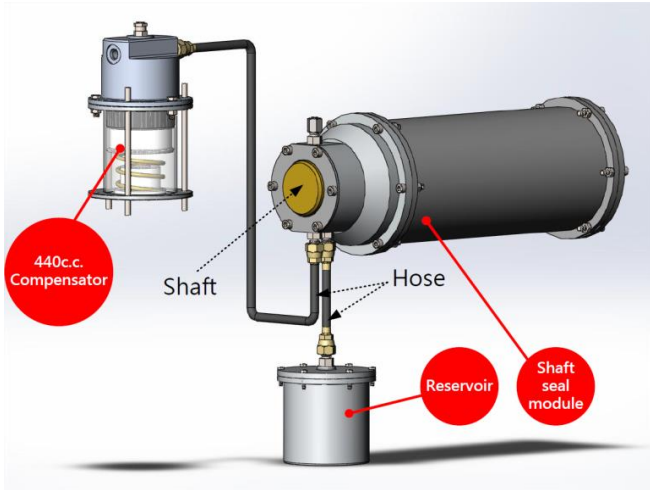

Fig. 2 Passive oil compensated shaft seal module (1/25 scaled). Consisted of 440 c.c. passive oil compensator, shaft seal module and reservoir. The characteristics of high reliability, maintenance free and adapted to different water column would help enlarge FKT working endurance.

Fig. 3 is the structural diagram of the traditional rubber diaphragm integrated piston oil compensator, the steady-state equation of the piston assembly is:

$$\Delta P_c = P_c - P_a = \frac{k_s(x_0+x_c)-m_c g}{A_e}, \tag{1}$$

In which

$$A_e = 0.7854\left(D_c\frac{D_c-D_p}{2}\right)^2 \tag{2}$$

where ΔP_c stands for the pressure difference between internal oil of the compensator and outer sea water, P_a is the pressure of sea water, k_s is the spring stiffness, x_0 is the spring pre-compression when the piston is at the neutral plane, x_c is the piston displacement from the neutral plane, A_e is the effective action area, D_c and D_p are the cylinder diameter and piston diameter, respectively. Once the compensated oil total volume is selected, the rubber diaphragm dimension can be determined accordingly. The design of the compensator main structure and piston could be finalized as well. Finally, an appropriate spring for the compensator could be chosen in accordance with the design pressure differences between internal oil and ambient pressure.

Due to the small oil compensated volume in the 800 W FKT shaft seal module, the total compensation volume of the compensator is determined to be 440 c.c.. The rubber diaphragm uses Class 4 Top Hat diaphragm from Bellofram, which is compressed with woven fabric and elastomer to accommodate tension and rolling environments, and the effective action area A_e is chosen to be 41.01 cm^2. To prevent water ingress from failure shaft seal, the compensation pressure is designed slightly higher than the ambient pressure between 2 to 14 psi, which corresponds to pressures at the piston top dead center and bottom dead center, respectively.

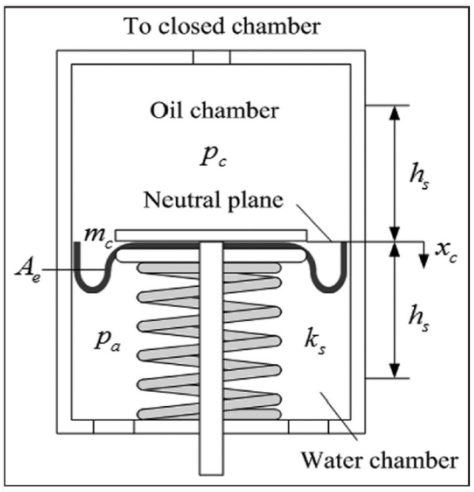

Fig. 3 *Structural diagram of the* traditional rubber diaphragm integrated *piston oil compensator.*

Thus, the spring stiffness k_s could be calculated from Eqs. (1) and (2), which is 3.87 kg/cm. The spring is made of stainless to adapt ocean environments and the free length and wire diameter are 150 mm and 4 mm, respectively. To avoid influence to the spring performance, the piston will be made of Teflon to reduce weight to 133 g. As shown in Fig. 4, the simulation result of the 440-c.c. compensator performance is consistent with original design.

The 440-c.c. compensator is made of 6061-T6 aluminium, the spring and piston are covered by transparent acrylic tube for an easy oil volume examination. For safety, a 15-psi relief valve is installed on the top of the compensator to prevent diaphragm explosion from inflated overheated oil. The key components of the compensator are shown in Fig. 5 and Fig. 6.

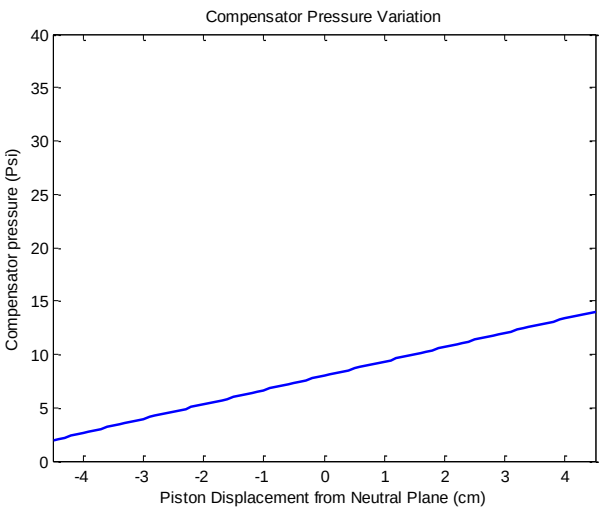

Fig. 4 *Simulation of the 440-c.c. passive oil compensator. Assume that the neutral plane is zero and piston is positive downwards, output pressure is 2 psi while the piston is at top dead center (-4 cm) and 14 psi while the piston is at bottom dead center (4 cm). This is consistent with the original design.*

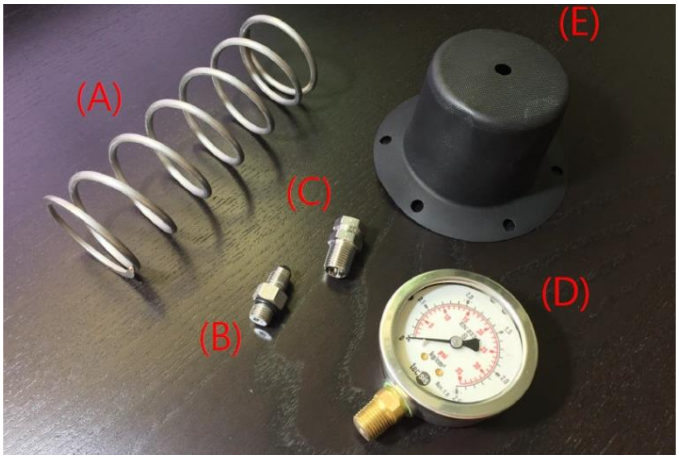

Fig. 5 *Key components of 440-c.c. passive oil compensator. (A) Stainless spring, (B) Hydraulic fitting, (C) 15 psi relief valve, (D) Pressure gauge and (E) Bellofram rubber diaphragm.*

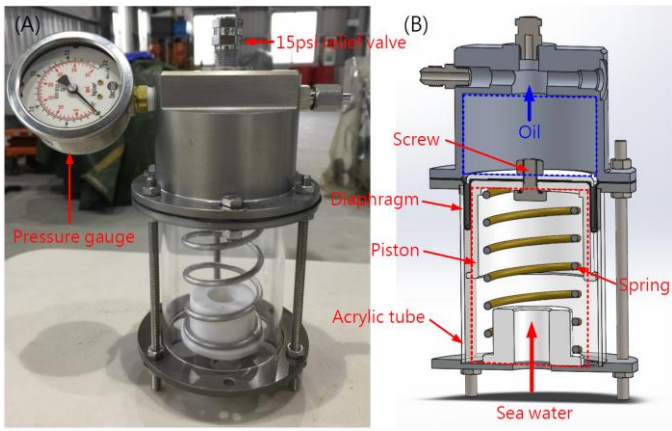

Fig. 6 *The 440-c.c. passive oil compensator. (A) Photo of compensator; (B) Section diagram of compensator.*

B. Design of Shaft Seal Module

The 800-W FKT shaft seal module utilizes a SUS316 rotating shaft with a diameter of 6 cm, the surface roughness and hardness of the shaft are chosen as Ra 0.3 μm and HRC 45, respectively, for better sealing performance. As shown in Fig. 7, three shaft seals are used in the module to separate sea water/oil, oil/air and air/air, respectively. The Teflon spacer will be used to isolate each chamber between two shaft seals, and the chamber between seals A and B will be filled with compensation oil. There are three ports drilled on the module for compensation oil inlet, oil case drain and venting air. The venting port is used to exhaust air to ensure no air remained in the chamber seal A/B. NAK seal, which is manufactured in Taiwan, is used as shaft seal according to the evaluation of FKT working environment. The section diagram of shaft seal is shown in Fig. 8. The shaft seal is made of Fluorocarbon Rubber, which has a great chemical property and a wide working temperature ranging from -25ºC to 250ºC. To reinforce the stiffness, SUS 316 stainless is used as the main support ring and a stainless garter spring is also integrated in the seal lip to smooth the contact surface and to improve the

sealing capability. In addition, a tapered roller bearing is used as the main rotating interface of the shaft seal module to minimize the vibrating interference to the seal lip. The special tapered roller design would help to sustain axial and radial loads on the rotating shaft, therefore the working endurance of the shaft seal could be extended. The shaft seal assembly is shown in Fig. 9.

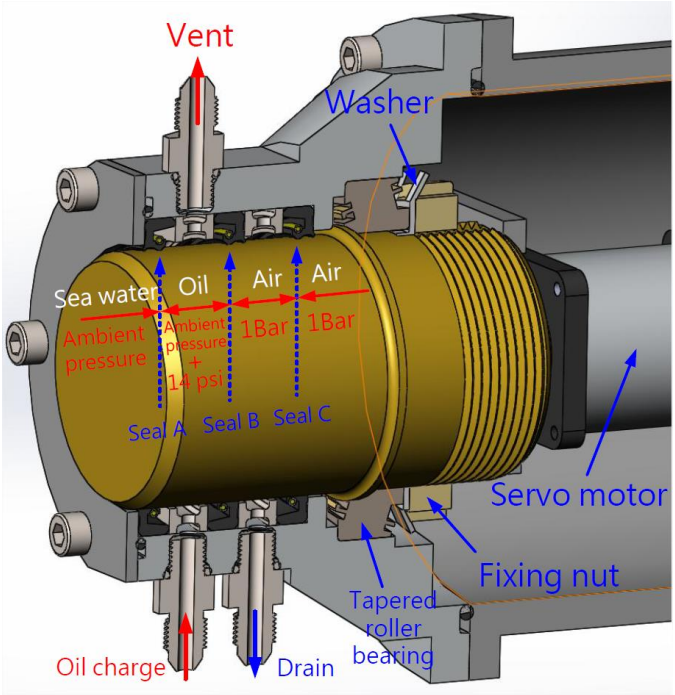

Fig. 7 *The section diagram of the shaft seal module. 3 shaft seals are used to isolate sea water/oil, oil/air and air/air. The tapered roller bearing could minimize shaft rotating deviation and reinforce the shaft axial and radial loading affordability.*

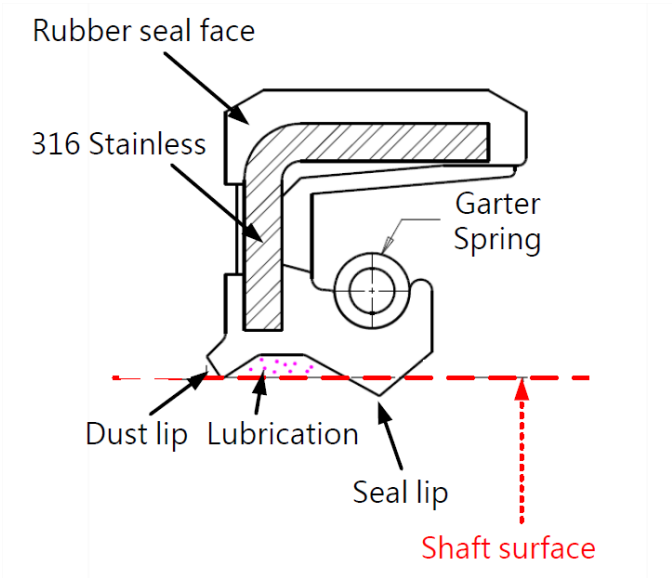

Fig. 8 *The section diagram of the NAK shaft seal. The shaft seal is mainly made of Fluorocarbon Rubber, and the internal SUS 316 stainless support ring and dust lip are integrated within the seal to enlarge working performance.*

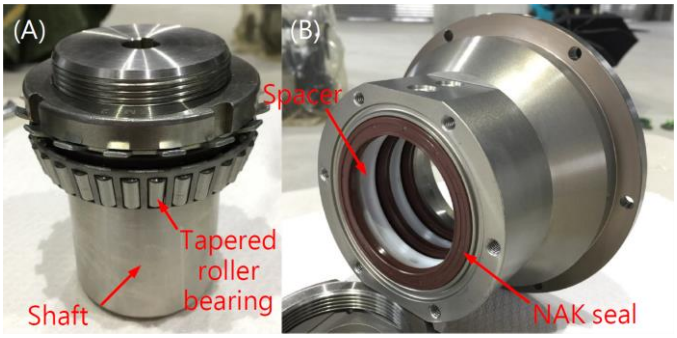

Fig. 9 *Photo of shaft seal module. (A) Shaft and tapered roller bearing; (B) The module housing and NAK shaft seals.*

C. System Integration

Fig. 10 shows the passive oil compensated shaft seal module, which includes a 440-c.c. oil compensator, a shaft seal module and a reservoir. The compensator is connected with the shaft seal module by hydraulic hose, and the oil pressure in chamber seal A/B could be balanced with ambient water pressure by the interaction of piston and pre-compression spring in the compensator. Meanwhile, the pre-compression spring provides a additional pressure from 2 to 14 psi above the ambient environment; this is a protection mechanism to exhaust oil in advance in case severe wear is happened onto the shaft seal. The shaft seal module is also connected with a reservoir to store leaking oil from the module. From the oil volume of the compensator, the health condition of the shaft seal module could be monitored. If the oil level decreases gradually, FKT need to be inspected and repaired immediately for a long time operation.

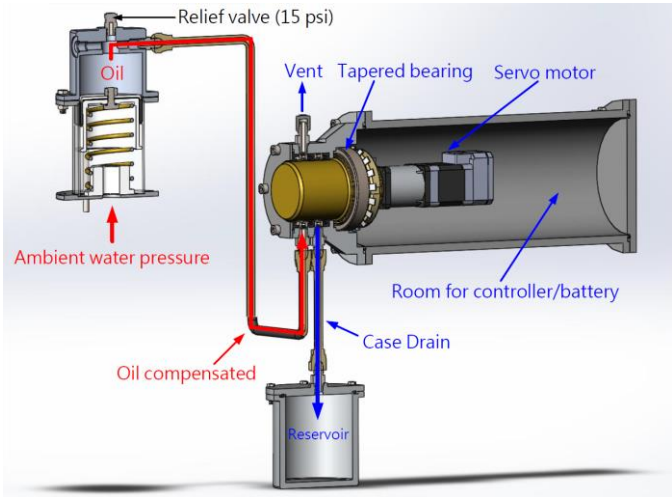

Fig. 10 *The passive oil compensated shaft seal module.*

III. Test of Passive Oil Compensated Shaft Seal Module

Prior to the system test, every component should be examined individually to check if its performance meets the original design. Therefore, there are several tests need to be conducted, including pressure test for 440-c.c. oil

compensator, sealing test for shaft seal module, pressure test and sea trial for passive oil compensated shaft seal module. Each test are detailed in the following.

A. *Test of 440 c.c. Oil Compensator*

A pressure gauge is installed onto the compensator to provide actual spring output pressure in different oil level as shown in Fig. 11. The compensator is charged by a hydraulic pump and a ball valve is used to isolate compensator and pump while measuring spring output pressure in different amount of compression. The test result is fitted with simulation as shown in Fig. 12, following the increase of spring compression the spring output pressure is linearly raised. The 15 psi relief valve is also functional after test, which could release oil to avoid further damage if compensator is overloaded. In general, the performance of 440 c.c. oil compensator is consistent with design.

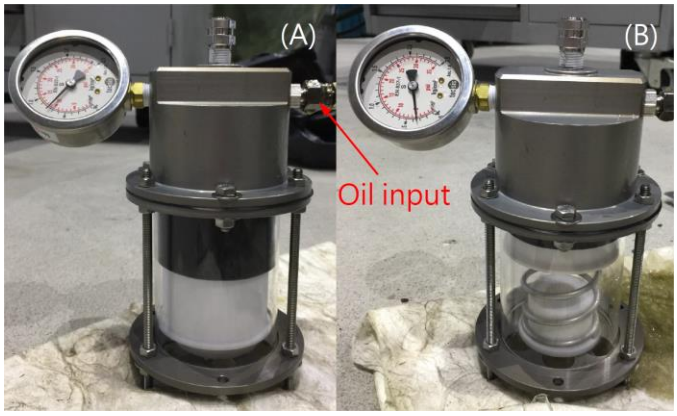

Fig. 11 *Test of 440 c.c. passive oil compensator. (A) Oil volume is 90%; (B) Oil volume is 25%.*

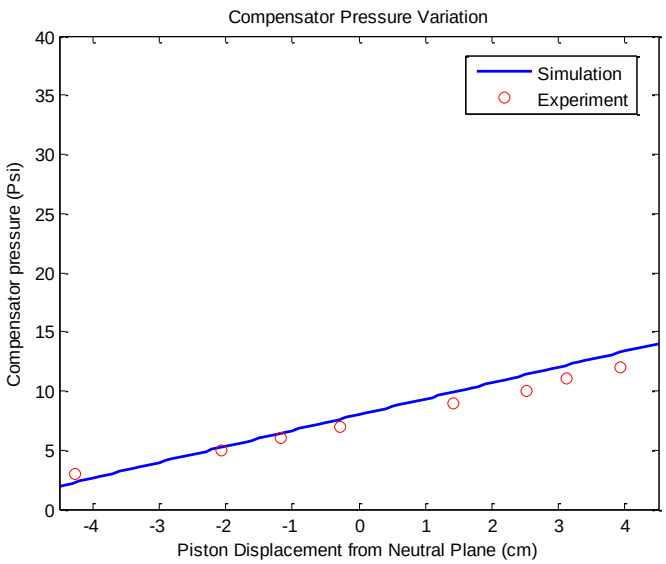

Fig. 12 *Performance of 440 c.c. oil compensator. The experiment result is consistent with original design, the output pressure is ranged from 2 to 14 psi.*

B. *Sealing Test of Shaft Seal Module*

All the O-rings of the shaft seal module should be tested prior to conducting pressure test, this is to make sure the final pressure test is completely focused at the performance of shaft seal. Thus, a vacuum pump is used to do the subatmospheric test as shown in Fig. 13. The shaft need to be removed from the shaft seal module and a cover is used to cap the shaft cavity, and the shaft seal module is connected to the vacuum pump through a negative pressure gauge and a ball valve. The air in the shaft seal module will be extracted until pressure gauge reading is -480 mmHg (about -0.63 ATM) and then shut the ball valve for 20 mins, the internal pressure could be held without leaking. This indicates all O-rings are working properly during the test, and the final pressure test could be proceeded. If water is observed in the shaft seal module during pressure test, the NAK seal might be failed.

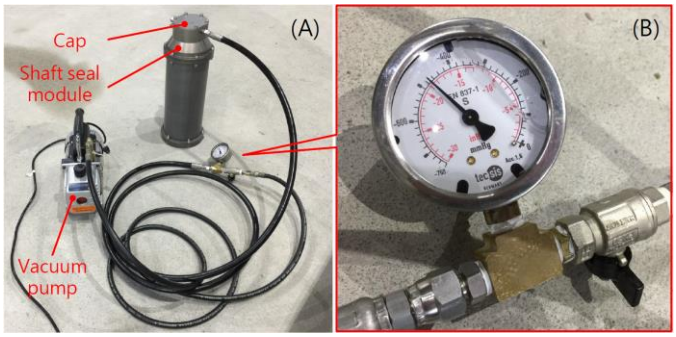

Fig. 13 *Sealing test of the shaft seal module. (A) Testing mechanism; (B) Reading from pressure gauge is -480 mmHg.*

C. *Pressure Test of Passive Oil Compensated Shaft Seal Module*

The system is physically integrated for the following pressure test as shown in Fig. 14. A servomotor powered by lithium battery is used to drive shaft directly at about 10 rpm to simulate rotation of KFT shaft, and the passive oil compensator is charged to 80% full (about 360 c.c.). To make sure nothing will be going wrong, the passive oil compensated shaft seal module is placed into a bucket for 1 hour with rotating shaft is powered. Compared to beginning, the oil volume in the end is exactly the same as original after 1 hour experiment. This proves passive oil compensated shaft seal module could be working properly. A shallow water test at a 8-m depth is also completed at the water tank of NTU ESOE department; no evidence of water ingress is observed in the shaft seal module.

Since the target working water depth is 30 m and 50 m for 20-kW and 0.5-MW FKT, respectively. Therefore, it is essential to withstand pressure up to 100 m (about 11 Bar) for passive oil compensated shaft seal module. In addition to conduct the pressure test in an open water, a pressure vessel is efficient and convenient for doing the similar test. The pressure vessel could accommodate all components of the

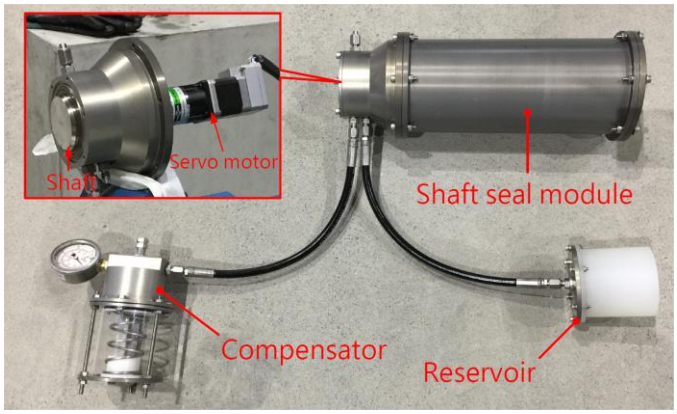

Fig. 14 *1/25 scaled passive oil compensated shaft seal module. The shaft is driven by a servomotor at 10 rpm, and the power is supplied by two lithium batteries.*

module, which is made of SUS 304 stainless, inside diameter is 250 mm, height is 1000 mm and thickness is 10 mm. An external pressure gauge, pressure inlet port and relief port is integrated to the pressure vessel for verifying testing pressure. To simulate the shaft seal module pressurized by uniform force in the ocean, the module is placed inside the water filled pressure vessel and pressurized by external high-pressure air. First, the pressure vessel is pressurized to 6 Bar (equivalent to a 50-m water depth) for 10 minutes, and no water is observed after the experiment. The oil volume remains at the same level and the shaft keeps rotating steadily. The second test is then conducted with the same setting and the inlet pressure is increased to 11 Bar (equivalent to a 100-m water depth), the shaft seal module is able to work without any leakage after 25-minute test. After pressure tests, the performance of passive oil compensated shaft seal module is confirmed.

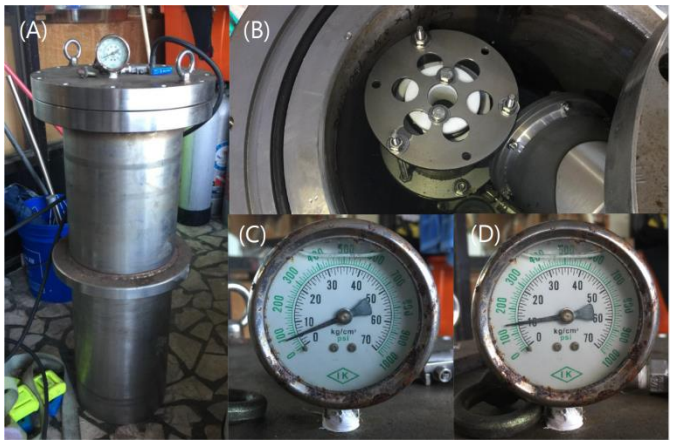

Fig. 15 *Pressure test of passive oil compensated shaft seal module. (A) The pressure vessel; (B) Water is filled into the pressure vessel and pressurized by high pressure air to simulate ocean environment; (C) Pressure gauge reading is 6 Bar (equivalent to 50 m water depth); (D) Pressure gauge reading is 11 Bar (equivalent to 100 m water depth)*

D. Sea Trial of Passive Oil Compensated Shaft Seal Module

In addition to the pressure vessel, a sea trial is also finished. A stainless frame is added for the passive oil compensated shaft seal module to improve safety of deployment and recovery, and a GoPro camera is also installed to record the testing process as shown in Fig. 16. The passive oil compensated shaft seal module is connected to a 100-m long cable and deploy into ocean for 30 minutes, the estimated operating depth is about 50 to 70 m due to local ocean currents. Fig. 17 shows the image obtained by GoPro. No leakage is observed after recovering the system. Based on the test result of the pressure vessel and sea trial, all functions of the passive oil compensated shaft seal module are consistent with the original design.

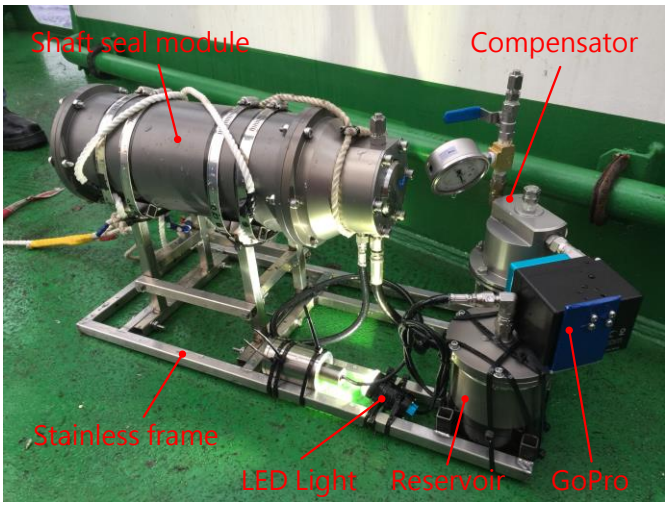

Fig. 16 *Passive oil compensated shaft seal module.*

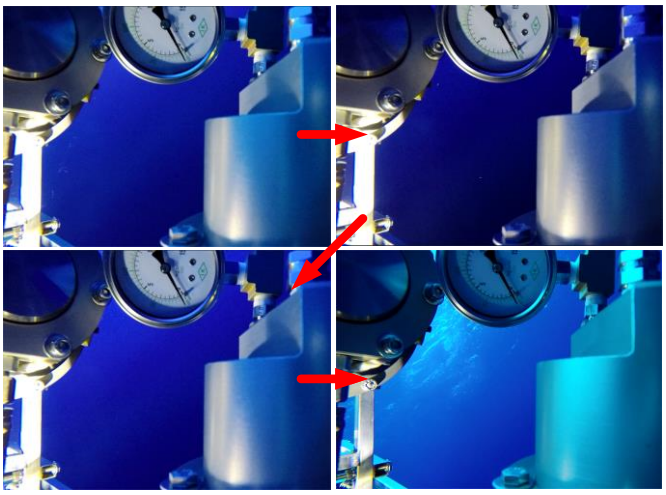

Fig. 17 *Image obtained by GoPro during the sea trial.*

IV. Conclusions

The FKT dedicated passive oil compensated shaft seal module is inspired by the ROV compensation system, which has finished module design, fabrication and pressure test. From the result of tests, the performance such as 440-c.c. oil compensator output pressure and the seal capability of shaft seal module are all consistent with the original design. Therefore, the passive oil compensated shaft seal module would only need to be slightly modified for integrating into the 20-kW or 0.5-MW FKT unit. For the commercial FKT

unit, an oil volume monitoring system is recommended to add since the oil volume is positively related to the condition of shaft seal. The oil volume decreases in accordance with the leakage of the bad shaft seal, so the system maintenance should be scheduled as soon as possible once the volume is lower than a certain level. This safety mechanism will be an important factor for a quick system healthy evaluation in the future.

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