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Analysis and modelling of a novel hydrostatic energy conversion system for seabed cone penetration test rig

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ABSTRACT

The energy supply is a key issue for underwater equipment used in seabed exploration, especially in deep water. The high-pressure seawater in deep water contains massive hydrostatic energy and it is a potential clean energy source. The type of energy has advantages of low cost and relatively high reliability in deep water. A novel drive system which converts seawater's hydrostatic energy to mechanical energy is proposed for seabed cone penetration test rig. The hydrostatic drive system uses variable displacement hydraulic motor and PID control method to ensure stabilization of penetration speed and high energy efficiency. The mathematical model of the drive system is built and the comprehensive analysis is conducted. The analysis results based on the real resistance data indicate that the drive system can keep the penetration speed stable when encountering severely fluctuating sediment resistance at different depth of water and achieve high energy efficiency. The mathematical model is validated by the comparison of the results of mathematical model with simulation model based on the commercial software. Because of the high efficiency, the drive system can output considerable amount of energy which is comparable to underwater large battery pack carried by present deep-water cone penetration test rig.

1. Introduction

Cone penetration test (CPT) is an in situ test method to provide the sediment information for establishing stratigraphic profiles in the design of offshore foundation and many other offshore applications. Because it can continually measure the in situ data of sediment profile at seabed, it is more accurate and efficient than the conventional seafloor sediment sampling. Currently, it has become an essential part of offshore soil investigation for decades, and most requirements are from the oil and gas industry (Randolph, 2016; Lunne, 2012). With the increasing requirement of exploration of offshore oil and gas and geohazard assessments in deeper water, CPT need to meet the challenge brought by the deep water and ultra-deep water such as the energy supply, reliability and cost-efficiency (Boggess and Robertson, 2011).

There have been commercial seabed CPT rigs in the market such as the ROSON series, the Neptune series, the Manta series and Seacalf series. The rigs work within 3000 m of water depth and are powered by the electric energy transmitted through the umbilical cable from the surface vessel (Lunne, 2012). The drive system of the rigs include underwater unit and surface support unit. The underwater unit comprises electrical cable, underwater power transformer, hydraulic drive pack and electrical motor. The unit on the surface vessel is mainly a special winch which play the role of deploying the rig and transforming the electrical energy of the vessel to the umbilical cable. Because of the complexity of the drive system, its cost and requirement for capability of support vessel is relatively high, especially for heavy CPT rigs. As to CPT rigs capable of working at depth of 3000 m–6000 m such as the Penfeld CPT rig (Meunier et al., 2004, 2005), the drive system is powered by the battery packs rather than the electricity transmitted through umbilical cable because the long distance of electrical energy transmission will cause great energy loss and significant increasing of the difficulty of deployment of the rig. The lead battery of Penfeld rig is contained in a pressure-compensated box that is full of oil. The electricity of the battery is transformed by a power invertor and is supplied to electrical motor and hydraulic power pack. In terms of the reliability, both types of the CPT rig use many underwater electrical components such as power invertor, transformer, electrical motor and battery pack, which make the rig costly and vulnerable to water leakage.

The hydrostatic energy of seawater, also known as pressure energy, provides an alternative to power CPT rigs, especially in deep and ultra-deep water. There is about 1.1 kWh of hydrostatic energy stored in 100 L of seawater at depth of 4000 m, and the amount is equal to the capacity of lead battery packs of Penfeld rig. The power density of the hydrostatic energy increases linearly with the depth of water, which

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highlights its advantage in deep and ultra-deep sea. Because the hydrostatic energy is derived from mighty pressure of the seawater, it is available around the worldwide ocean and is also clean. In practice, the hydrostatic energy can be mobilized by mounting low-pressure or evacuated chambers on CPT rigs. The pressure difference between ambient high-pressure seawater and the low-pressure chamber is used to drive the rig. The existence of low-pressure chambers increases the weight of CPT rigs, but the weight of chambers doesn't penalize the rig, as the rig must be heavy enough to react during the penetration of rig's rod which contains sensors inside the tip. Besides, the hydrostatic drive system is more robust and cheaper because many electrical components such as power transformer, large battery packs, umbilical electrical cable and electrical motor are not needed any more. The deployment efficiency of the CPT rig can also be improved.

During the penetration of rig's rod, the sediment resistance fluctuate severely due to the complexity of the stratigraphy. In order to collect raw data of high quality in the situation, the penetration speed of the rod with sensors in the tip is required to keep steady at a certain speed during the test such as 2 cm/s. This brings challenge to the CPT rig powered by the hydrostatic energy of seawater. Till now, the seawater's hydrostatic energy have been used to power the seafloor sediment sampler (Kristoffersen et al., 2006; Smits, 1990; Wang et al., 2013; McCoy and Selwyn, 1984; Selwyn and McCoy, 1981; Wang et al., 2017; Wang et al., 2012), the seabed rock driller (Brooke and Gilbert, 1968), the underwater electrical generator (Wang et al., 2008) and the marine life tag (Shafer et al., 2015). However, the hydrostatic energy conversion systems of above underwater equipment are not capable of handling the seabed cone penetration testing with high efficiency. A patent of CPT rig that is powered by the hydrostatic energy of seawater was proposed (Bienvenu and Bessonart, 2001). In the patent, a flow control valve is used to stabilize the penetration speed. Although the flow control valve can keep the speed steady, the efficiency of the system is low because a large amount of energy is lost at the control valve. Especially when the sediment resistance stay low, the vast majority of the hydrostatic energy will be lost. Thus, the patent haven't been used in practice (Lunne, 2012).

Based on above analysis, a new drive system powered by the hydrostatic energy of seawater is proposed for the CPT rigs in deep water or ultra-deep water. The drive system uses a variable hydraulic motor to convert the hydrostatic energy into mechanical energy of the rod. The mechanism of adjustable displacement of the hydraulic motor combined with control method enable the penetration speed of rod to keep steady. The utilization of the variable displacement hydraulic motor make the system achieve much higher energy efficiency than the method using flow control valve though the mechanism of variable displacement slightly increases the cost and complexity. The structure of the drive system is firstly described, and then its mathematic model is built. Based on the mathematical model, the comprehensive analysis is conducted, including the stability analysis and boundary of maximum speed error of rod and the damping of the system. Finally, the analysis based on the real penetration resistance data collected in sea trial reported in the reference is conducted, and then the results are discussed and verified by the results based on the commercial software.

2. Structure of hydrostatic drive system for CPT rig

Fig. 1 depicts the simplified structure of CPT rig driven by the hydrostatic energy of seawater. The drive system pushes the rod into seabed sediment during the test and pulls out the rod during the retrieval. The flexible rod is of tens of meters and coil around a drum. The coiled rod is straighten by the force of drive system during the penetration and bend to fit to the drum during the retrieval. The drive system consists of a hydraulic subsystem and a mechanical subsystem. The hydraulic subsystem comprises a variable displacement hydraulic motor, a direction valve pack, the low-pressure chambers and a filter. The mechanical subsystem comprises a flywheel, a decelerator, a drive chain and several friction wheels. The hydraulic subsystem converts the hydrostatic energy of seawater into the rotational kinetic energy of the motor, which is then passed to the rod by the mechanical subsystem.

Fig. 2 illustrates the working principle of the hydraulic subsystem. The high-pressure seawater flows through the filter and the direction valve into the hydraulic motor. The direction valve control the rotational direction of the hydraulic motor and also the direction of the rod's motion. The motor rotates under the pressure difference between the high-pressure seawater and the air in low-pressure chambers. After flowing through the motor, the seawater is depressurized and drained into the low pressure chambers. When seawater flows into the chamber, the air in the chamber is compressed and the pressure difference between the inlet and outlet of the hydraulic motor decrease. When the pressure difference decease to zero, the hydrostatic energy of the rig is exhausted and the drive system stops.

During the penetration, the sediment resistance on the rod fluctuates severely and is transferred through the mechanical subsystem to the hydraulic motor. To accommodate to the fluctuating resistance and keep the rotation speed stable, the variable displacement mechanism of the hydraulic motor is controlled to changes the displacement of the motor according to the variation of rotational speed caused by the fluctuation of resistance. A flywheel is added to help stabilize the rotation speed. According to Eq. (1), the driving torque of the hydraulic motor can be adjusted to balance the fluctuating resistance torque by changing the displacement of motor so as to keep the rotational speed stable.

$$T_d = \frac{\Delta PD}{2\pi}\cdot\eta_{Mm} \tag{1}$$

where T_d is the drive torque of hydraulic motor, ΔP is the pressure difference between the inlet and outlet of hydraulic motor, D is the displacement of the motor and η_{Mm} is the mechanical efficiency of hydraulic motor.

The control diagram of the drive system is shown in Fig. 3. The set speed is the required penetration speed of the rod, and the actual speed of the rod is obtained by converting the measured rotation speed of hydraulic motor based on simple kinematic relation between the motor and the rod. The speed error between the set speed and actual speed is used as the input of controller. According to the control signal, the hydraulic motor change the drive torque through adjusting the displacement of hydraulic motor to balance the sediment resistance torque and keep the rod's speed stable.

3. Modelling of hydrostatic drive system

The hydrostatic drive system is divided into subsystems which are modelled separately. Then, the models of subsystems are assembled to form the whole model.

3.1. Modelling of hydraulic subsystem

The model of hydraulic subsystem is built to get the quantitative relation of the control signal and the drive torque of hydraulic motor. The drive torque of hydraulic motor is determined by the pressure difference and the displacement of motor according to Eq. (1). The pressure difference is differential between the seawater's pressure and air pressure in low-pressure chambers.

$$\Delta P = P_s - P_a \tag{2}$$

where P_s is the pressure of ambient seawater and P_a is the air pressure in low-pressure chambers.

When the seawater flows into the chamber, the air in the chambers is compressed. Because of relatively low compression rate and high heat conductivity of stainless steel of the chamber, it is assumed that the air in the chamber goes through an isothermal compression (Chen et al., 2007). Therefore, the air pressure in the chambers is calculated as