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Simulation and analysis of a seawater hydraulic relief valve in deep-sea environment

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ABSTRACT

Considering the deformation of a designed seawater direct-acting relief valve (SDARV) in deep-sea environment, which has a significant influence on the dynamic performance, the mathematic model of SDARV was established and related dynamic characteristic simulations were conducted. Since the fit clearance between damping spindle and damping bush is the key parameter affecting the dynamic characteristic of SDARV, the different fit clearances against varying depths were studied by ANSYS Workbench. The variations of seawater properties at different sea depths were also introduced to investigate the effect. From this study, the valve's dynamic performance after optimization in deep-sea environment was researched by MATLAB and the effective sea depth suiting for normal work was got. The results indicated effective dynamic performance of the SDARV within the depth of 1700 m and the optimum fit clearances after deformation should be kept in the range of 0.019 mm to 0.045 mm in deep sea environment.

1. Introduction

In recent years, more and more countries have focused their attention on technology in deep-ocean resource exploitation (Meinig et al., 2001; Yuh, 2000). It has become the hotspot in research and application of fluid power transmission and control to directly use seawater or fresh water as working medium, because water hydraulic transmission has advantages of environmental friendliness, non-flammability, no pollution, convenient maintenance and low operating cost (Lim et al., 2003). Above all, environmental friendliness makes it possible for seawater hydraulics to work as open-circuit system (Yinshui et al., 2009; Yang et al., 2015) without return lines and reservoirs. However, the deep-sea environment is greatly different from the sea at surface. It is characterized by total absence of sunlight, high hydrostatic pressure (it increases 1 atm for each 10 m in depth), and a low water temperature about 3 °C, apart from hydrothermal vent fields where the temperature of water maybe as high as 400 °C (Traverso and Canepa, 2014). The complicated environment will lead to variations in seawater properties, such as the density, the bulk modulus of elasticity and the coefficient of dynamic viscosity. All these severe conditions will be great challenges for the hydraulic components. Especially, high hydrostatic pressure in deep-sea environment will make hydraulic components produce large deformation (Yuan and Wu, 2014), which has a serious effect on the hydraulic system.

Almost every hydraulic system is equipped with a pressure relief valve to maintain the working pressure of the system at a pre-determined level and protect the system from overpressure. There are two types of valves that are available: direct and pilot type (Dasgupta and Karmakar, 2002a, 2002b). Compared with the pilot operated relief valve, the structure of direct-acting type is more simple, and the operative state is more stable and reliable (Bazsó and Hős, 2013). Besides, for the direct type, the leakage is less and the seal control is really easy. Therefore, such direct operated relief valves using seawater as the working medium are frequently used (Suzuki and Urata, 2008). However, there is a potential risk of failure while the SDARV working in deep-sea environment. For example, the valve may be subjected to wear and abrasion and even get stuck because of the silt suspending and other seawater impurity (Wu et al., 2016), and the corrosiveness of the seawater will cause the structural damage and the seal damage of the valve. Besides, the higher vapor pressure and the faster flow speed of seawater will lead to the effect that cavitation erosion and vibration is easier to occur in the SDARV. Above all, high hydrostatic pressure in deep-sea environment will lead to worse performance of the valve or even failure because of the large deformation.

This paper presents a SDARV designed by the author, which has been successfully used in mobile underwater tool system driven

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Nomenclature

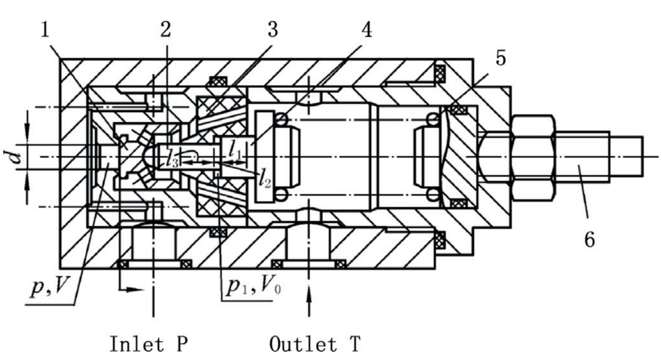
C_q	flow coefficient of the valve port
C_v	velocity coefficient of the valve port
μ	dynamic viscosity of seawater (Pa s)
ρ	seawater density (kg/m^3)
β	bulk modulus of seawater (MPa)
d	diameter of the valve port (mm)
d_1	diameter of the front-end damping spindle (mm)
d_2	diameter of the back-end damping spindle (mm)
δ_1	fit clearance between front-end damping spindle and damping bush (mm)
δ_2	fit clearance between back-end damping spindle and damping bush (mm)
l_1	fit length between front-end damping spindle and damping bush (mm)
l_2	fit length between back-end damping spindle and damping bush (mm)
l_3	initial length of damping chamber (mm)
m	equivalent mass of motion part (g)
p_s	nominal working pressure (MPa)
K	stiffness of the spring (N/mm^2)
x_0	pre-compression of the spring (mm)
x_s	the displacement of the spring at p_s (mm)
V	pipeline volume from the pump to the valve port (L)
P	inlet pressure (MPa)
p_1	pressure in the damping chamber (MPa)
A	flow area of the valve port (mm^2)
A_1	effective area of front-end damping spindle (mm^2)
A_2	effective area of back-end damping spindle (mm^2)
B_1	damping coefficient of front-end damping spindle
B_2	damping coefficient of back-end damping spindle
q_1	flow rate through the clearance between the front-end damping spindle and damping bush (lpm)
q_2	flow rate through the clearance between the back-end damping spindle and damping bush (lpm)
V_1	initial volume of the damping chamber (L)
Δq	flow rate of the pump (lpm)
q	flow rate through the valve port (lpm)
T	outlet of the valve
tr	the rise time (s)
tp	the peak time (s)
Mp	the maximum pressure overshoot
ts	the setting time (s)

by seawater hydraulic power (Liu et al., 2010, 2008). With the consideration of the deformation of the valve in deep-sea environment, the mathematic model (Darby, 2013) of the valve is presented in this paper, and the related simulations of dynamic characteristic are investigated. Since the fit clearance between damping spindle and damping bush is the key parameter of affecting its dynamic characteristic in deep-sea environment, the studies focus on the deformation of the damping bush. The different fit clearances against varying depths are analyzed. In addition, the variations in seawater properties are introduced. These results show effective sea depth and optimum fit clearances suiting for normal work of the SDARV.

2. Physical model of the SDARV

Fig. 1 shows the critical elements of the SDARV, which has the following features (Liu et al., 2010):

a) The valve spool employs a flat form, which takes advantages of the better flow capacity in the same conditions compared with the poppet valve. Therefore, the pressure regulation accuracy of the valve in deep-sea environment is improved.



1- Valve spool, 2- front-end damping spindle, 3- damping bush,

4- back-end damping spindle, 5- spring, 6- adjusting screw

Fig. 1. Structural diagram of the SDARV.

b) There are damper units including the damping spindle and damping bush in this valve to decrease impulse force and vibration. The machining operation of the stepped shaft is difficult, so the damping spindle consists of two parts, the front-end part and the back-end part to avoid the machining problem.

c) There is a cylindrical oriented surface on the valve spool, which can reduce the vibration resulting from the lateral swing after opening. Besides, there are four orifices in the cylindrical surface, which constitute a two-step throttle together with the valve port to restrain cavitation near the valve port.

d) The contact surface between the damping spindle and valve spool is spherical, which contributes to automatic centering of the damping spindle to avoid getting stuck.

Furthermore, anticorrosion alloy and engineering plastics are used in this valve to prevent seawater corrosion. For example, the valve spool is made of 17-4PH, the valve sleeve and the damping bush are made of PEEK, the valve body and the damping spindle are made of 316L, and the spring is made of 3J1 (Ni36CrTiAl). The rated pressure of the SDARV is 14 MPa, and the rated flow is 25 lpm.

3. Mathematic model of the SDARV

The following assumptions are accepted in the mathematical model describing the dynamic characteristics of the relief valve (Dempster et al., 2006; Dasgupta and Karmakar, 2002b; Luo et al., 2013):

1. The system overall is dynamically pressure balanced with the external seawater pressure, hence outlet gauge pressure can be assumed to be zero.
2. In the simplified model of this relief valve, the flow inertia and leakage of water in the relief valve are difficult to predict and have little effect on the dynamic performance, thus they can be disregarded.
3. The transient flow force is generally disregarded in relief valves