

Theoretical Study and Experimental Optimization on the Reliability of a Seawater Hydraulic Solenoid Valve

Shan Wu, Xufeng Zhao, Donglin Li, and Xiaohui Li

Abstract—As an important component of the variable ballast system (VBS), an key subsystem of submersible, seawater hydraulic solenoid shut-off valve(SSV) functions as a transport hub which controls the discharge and injecting of variable ballast cabin. Through theoretical analysis, temperature rise was found to be a main cause of the SSV's failure. In order to improve the reliability of the SSV, two experimental apparatus were built to test the characteristics of the solenoids and the reliability of the SSV. Result shows variable voltage driving is an effective way of reducing the failure, which can sharply restrain the temperature rise of the solenoids. Moreover, an optimal action cycle was found in which the solenoid valve has a longer continuous on-off time between failures (CTBF) and shorter response time.

Index Terms—Seawater hydraulics, variable ballast system, solenoid shut-off valve, failure analysis.

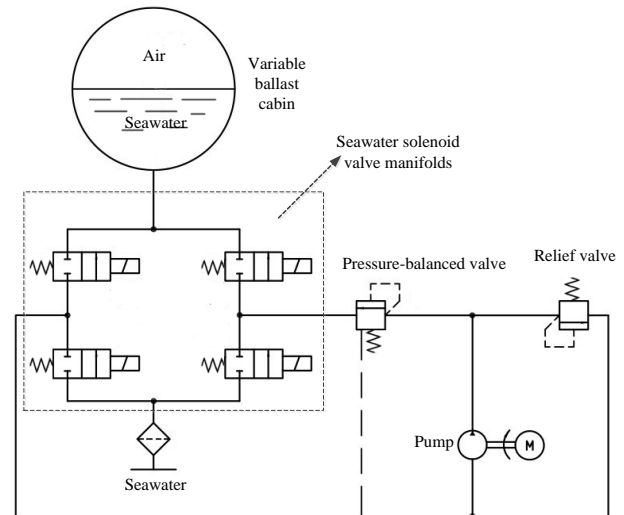


Fig. 1. Schematic diagram of variable ballast system.



Fig. 2. The appearance of the valve manifold.

I. INTRODUCTION

Manned submersible is a very important equipment for deep-sea exploration, the main mission of which is carrying scientists, engineers, various instruments and tools to the deep sea to perform tasks of exploration, scientific research [1]. During one dive, the total weight of the submersible often varies because of the change of the load in the scientific basket or the difference of seawater density at different depths or regions. The VBS is designed for the pilot to adjust the weight of the submersible while in the deep sea [2].

Fig. 1 shows the schematic diagram of a typical variable ballast system [3]-[5]. In the system, the seawater solenoid valves manifold is composed of four solenoid valves and controls the discharge and influxion of water from and to ballast cabin [6], [7]. The appearance of the valve manifold is shown in Fig. 2.

The reliability of the valve manifold is particularly important as it plays a key role in VBS. In this paper, the failure model of a single valve in the valve manifold will be analyzed theoretically and experimentally. In addition, the measures to reduce failures are presented and verified.

II. THEORETICAL ANALYSIS OF FAILURES

The failure of solenoid valve is mostly caused by temperature rise [8]. When temperature rises, the output force of solenoids will decrease and the frictions of solenoid valve will increase as a result of thermal expansion [9]. In order to learn more about the failures, the force of the valve poppet and temperature rise of the solenoid will be analyzed in this section.

A. Force on the Valve Poppet

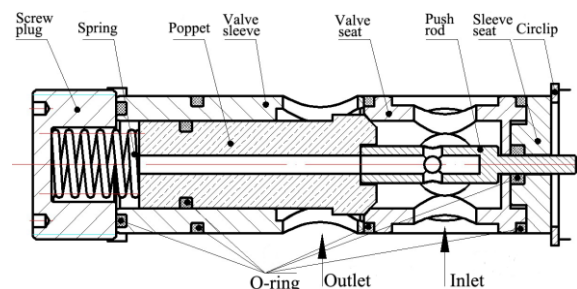


Fig. 3. Structure diagram of single solenoid valve.

Fig. 3 shows the structure of a single solenoid valve in the valve manifold [4]. The solenoid pushes valve poppet by means of the push rod which is shown in Fig. 3.

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According to Fig. 3, the force balance equation of the valve poppet can be:

$$ma = F + f_{in} - f_c - f_{out} - f_t \pm f_f - f_s - f_h \pm G \quad (1)$$

where, m is the weight of the moving parts, a is the acceleration of the moving parts, F is the force exerted by solenoid, f_{in} is the force on the poppet exerted by static pressure in the direction of inlet, f_c is the force on the poppet exerted by static pressure in the spring chamber, f_{out} is the force on the poppet exerted by static pressure in the direction of outlet, f_t is the force on the push rod exerted by static pressure, f_f is the total friction on the poppet, f_s is the Bernoulli force, f_h is force exerted by the spring, G is gravity of the moving parts.

Assuming that the initial force exerted by the spring is f_{h0} and the solenoid is in good condition, the force on the poppet should meet the given equation as follows:

In the state of shut-off:

$$f_{h0} + G + f_c > f_{in} \quad (2)$$

When solenoid is energized:

$$F_{min} - f_t + f_{in} > f_{h0} + G + f_c + \lambda f_f \quad (3)$$

In the opening process:

$$F - f_t + f_{in} > f_h + G + f_c + f_f + f_{smax} \quad (4)$$

In the state of fully open:

$$F_{max} - f_t + f_{in} > f_{hmax} + G + f_c + f_{smin} \quad (5)$$

When the solenoid losses power:

$$f_{hmax} + G + f_c + f_{smin} > f_{in} + \lambda f_f \quad (6)$$

In the closing process:

$$f_h + G + f_c + f_s > f_{in} + f_f \quad (7)$$

B. Temperature Rise of Solenoid

As the solenoid in SSV is a DC solenoid, the main cause of temperature rise is Joule heat [6]. The effect of Joule heat complies with Joule's law:

$$Q = (U^2/R)t \quad (8)$$

where Q is Joule heat, U is the energizing voltage, R is the resistance of solenoid. The relationship between Joule heat and temperature rise is:

$$Pdt = CGd\tau + \mu\sigma\tau dt \quad (9)$$

where P is the Joule heat of solenoid, $CGd\tau$ is the heat energy which rises temperature, $\mu\sigma\tau dt$ is the heat energy of heat exchange..

C. Cause of Failure

According to Eq. (3)-Eq. (7), the increase of friction which

is caused by thermal expansion leads to failures of opening operation and closing operation.

As temperature rises, the resistance of solenoid increases and the current through the solenoid decreases if the energizing voltage is kept constant. Since the electromagnetic force is proportional to ampere turns, the force exerted by solenoid decreases with temperature rising. Based on Eq. (3)-Eq. (5), the decrease of the force exerted by the solenoid leads to the failure of opening operation. The opening process of SSV is shown in Fig. 4. As the volume and the weight of SSV are limited, it is extravagant to select a larger solenoid which can completely meet the requirement in hot state. Therefore, it is important to find some improved measures to decrease the failure ratio of the volume-limited SSV.

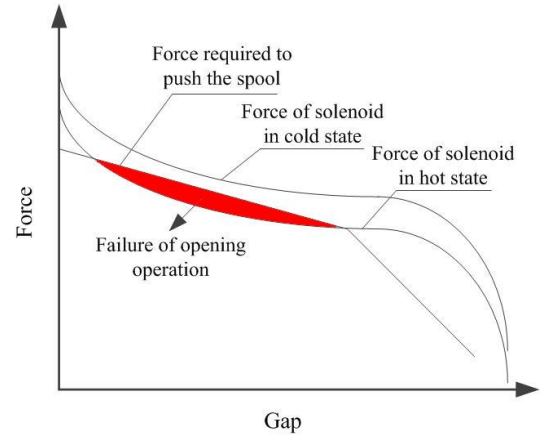


Fig. 4. Opening process of a single solenoid valve.

III. EXPERIMENTAL APPARATUS

In order to find some measures to improve the reliability of SSV, the experimental apparatus of solenoid and SSV were designed respectively.

A. Experimental Apparatus of Solenoid

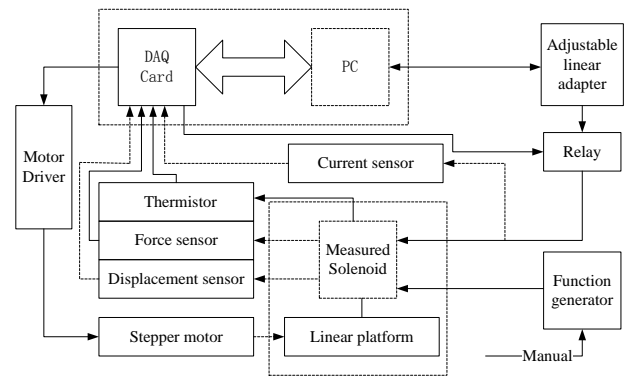


Fig. 5. System chart of solenoid experimental apparatus.

The system schematics of the experimental apparatus is shown in Fig. 5. The mechanical part of the apparatus consists of stepper motor, linear platform and mechanical bracket which are shown in Fig. 6. It supports all devices and can be used to adjust the length of solenoid's air gap according to the control signal. The control part consists of linear adapter, function generator, DAQ module, sensors, relay and measuring software. Measuring software collects

sensor signals through DAQ module to decide the next experiment parameters and generates experimental reports as well.

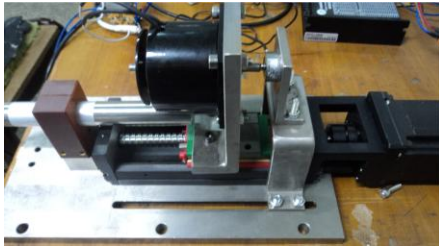


Fig. 6. Mechanical part of solenoid experimental apparatus

B. Experimental Apparatus of SSV

The hydraulic scheme of the experimental apparatus is shown in Fig. 7 which can set flow and pressure of the system by adjusting the throttle valve. In the experiment, experimental conditions were set to 2.4MPa and 25L/min which are the rated specifications of SSV. The measuring system controls the valve's on-off by USB-4711A DAQ card which connects a relay on the output port and diagnose the failures of SSV through the signals of a pressure sensor. If the pressure of the sensor is more than 0.2MPa in state of fully open, the valve is not fully opened and a failure of opening operation is figured. Similarly, if the pressure of sensor is less than 2.2MPa in state of shut-off, the valve is not fully closed and a failure of closing operation is figured. Experimental parameters such as action cycle, duty cycle, failure pressure and numbers of operations can be set in the programs.

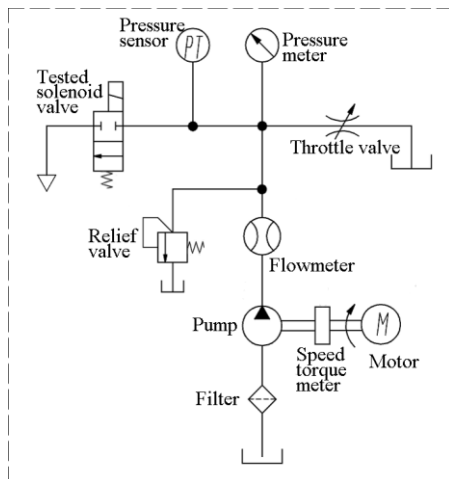


Fig. 7. Hydraulic scheme of valve experimental platform.

IV. EXPERIMENTAL RESULTS AND IMPROVEMENTS

Fig. 8 shows the temperature of solenoid has increased by 2.8 times in a continuous duty state after 45 mins, and the output force of the solenoid decreased by 40%. In fact, many existing measures of improving the reliability are based on restraining the temperature rise of solenoid. In the continuous duty state, variable voltage driving is a good way to improve reliability. Due to coupled response of valve and solenoid in the critical state, there is an optimal action cycle to ensure the rapidity and reliability of SSV in a continuous fast on-off state.

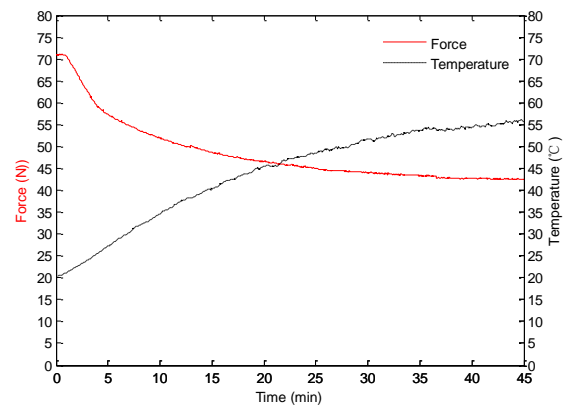


Fig. 8. Characteristics of a continuous energized solenoid.

The SI unit for magnetic field strength H is A/m. However, if you wish to use units of T , either refer to magnetic flux density B or magnetic field strength symbolized as $\mu_0 H$. Use the center dot to separate compound units, e.g., “A·m².”

A. Variable Voltage Driving

The force exerted by solenoid increases faster than the force required to push valve poppet in the opening process. Figure 9 illustrates the force required to push the valve poppet which is calculated by Eq. (2)-Eq. (7) and the force-displacement characteristics of the solenoid driven by different voltage which is measured at ambient temperature of 20 °C.

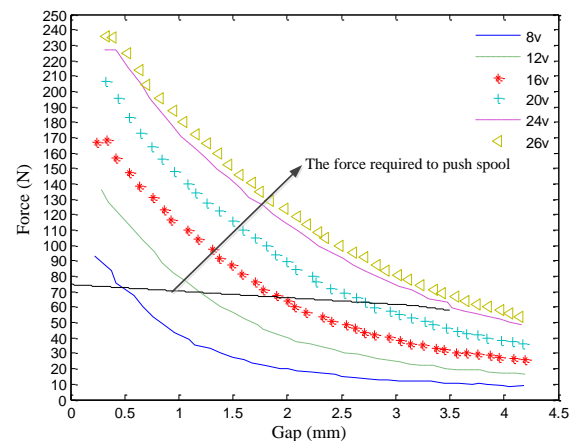


Fig. 9. Force of solenoid energized by different voltage.

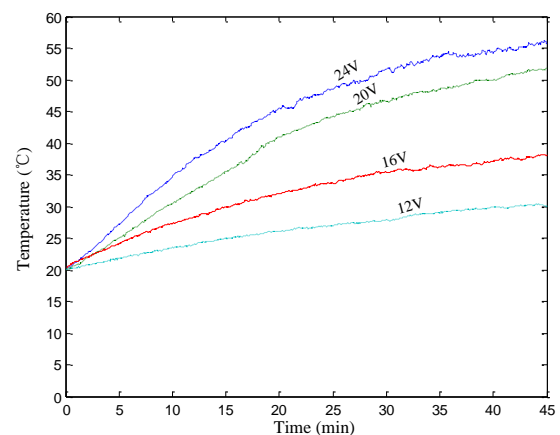


Fig. 10. Temperature rise of solenoid.

When the solenoid valve has been fully opened, it is inefficient to energize the solenoid by 24V voltage, since

12V energized voltage is able to provide sufficient force for maintaining the opening state. Higher energized voltage means more Joule heat which leads to temperature rise. Fig. 10 shows the temperature rise of a solenoid energized by different voltage for 45min at ambient temperature of 20 °C. The temperature rise of the solenoid energized by 24V voltage is 260% higher than that of the one energized by 12V voltage. Unquestionably, the way that opens the valve by a higher voltage and maintains the opening state by a lower voltage will effectively improve the reliability of SSV.

B. Optimal Action Cycle

Experimental results illustrating in Table I show that the continuous on-off times between failures (CTBF) of the solenoids operating with different action cycles and the same duty cycle are different from each other. The same duty cycle means the same size of Joule heat and the same cooling time. In theory, the temperature rise of the solenoid should be independent of action cycle under the same duty cycle. Experimental results in Table II which show the temperature rise of the solenoid energized by 24V voltage support this point.

TABLE I: CTBF OF 50% DUTY CYCLE (34°C)

Action cycle	Number of operations	CTBF
2s	450	15min
4s	762	50min48s
5s	677	56min25s
6s	595	59min30s

The critical state, in which the force exerted by the solenoid is close to the force required to push the poppet, a little fluctuation of electromagnetic force or the required force may cause failure of opening operation. When the solenoid is energized, the current through the solenoid increases rapidly. The changing current brings inductive effect which causes brief drop of the current [10]. As the force exerted by solenoid is positive related to the current through solenoid, there is a concomitant brief drop in electromagnetic force when the SSV is opening. Additionally, in critical state, the transient flow force which is neglected in the design is large enough to frustrate the opening operation. The transient flow force and the brief drop in the force exerted by solenoid lead to the delay in the opening operation in critical state. There is an obvious interrupt in opening operation when the solenoid valve was tested in critical state. A series of experimental results show that 4s is an optimal action cycle considering the rapidity and reliability simultaneously.

TABLE II: TEMPERATURE RISE OF 50% DUTY CYCLE (20°C)

Action cycle	10min	20min	30min
2s	5.3°C	9.2°C	11.3°C
4s	5.2°C	9.4°C	11.9°C
6s	5.0°C	9.4°C	11.9°C
10s	5.3°C	9.4°C	11.9°C

C. Improvements and Comparisons

Based on series of experiments, it was found that the following measures can significantly improve the reliability

of SSV:

- 1) Variable voltage driving: opens the valve by a higher voltage and maintains the opening state by a lower voltage;
- 2) Using the optimal action cycle;
- 3) Adding lubricating oil to the guiding sleeve of solenoid.

Table III shows the CTBF of the SSV with and without improvements.

TABLE III: COMPARISONS OF CTBF

Improvements	Number of Operations	CTBF
without	762	50.8min
with	3749	250min

V. CONCLUSION

Theoretical analysis and experimental results in this paper suggested that the temperature rise of SSV causes failure. Experimental results show that variable voltage driving can substantially restrain the temperature rise of the solenoid. In critical state, the brief drop in electromagnetic force and the transient flow force are the causes of delay in opening operation. There is an optimal action cycle which satisfies the requirements of both rapidity and reliability. The measures presented in this paper have been proven to be effective in reducing failures. In further, the coupled response of the valve and the solenoid need to be analyzed in detail to improve the response speed of SSV in critical state. In addition, the design of solenoid will be revised to restrain temperature rise.

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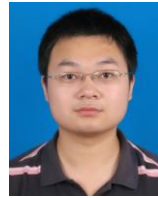
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