Ocean Engineering 163 (2018) 337–347

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Non-probabilistic reliability analysis and design optimization for valve-port plate pair of seawater hydraulic pump for underwater apparatus

Fanglong Yin, Songlin Nie*, Hui Ji, Yeqin Huang

Beijing Key Laboratory of Advanced Manufacturing Technology, Beijing University of Technology, Beijing 100124, China

ARTICLE INFO

Keywords:
Axial piston pump
Convex model
Non-probabilistic reliability
Reliability analysis
Seawater hydraulics
Valve-port plate pair

ABSTRACT

Seawater hydraulic axial piston pumps are widely used in underwater apparatus systems in recent years. Reliability of the valve-port plate pair is vital to the performance of seawater hydraulic axial piston pumps. As the distribution information of the material combinations and working conditions of seawater hydraulic axial piston pumps are insufficient, the probability reliability analysis methods are not available for the valve-port plate pair. This paper develops a non-probabilistic reliability convex model for the valve-port plate pair. Firstly, the rotation of the pump cylinder is partitioned into six stages. Based on this partition, the dynamic models of contact pressure and *pv* value (the product of contact specific pressure and linear velocity) of the valve-port plate pair are derived by accounting for the pre-compression angle. Secondly, the marginal interval for the limiting [*pv*] value (It is the usual criterion to evaluate the critical operating conditions under which the material fails) of the material combination was obtained through adhesive wear tests. Thirdly, a limit-state function is then established based on the stress-strength interference model. Finally, the analysis and sea test results indicate that the reliability of the valve-port plate pair has significantly improved by adding auxiliary support on the port plate.

1. Introduction

In the past two decades, seawater hydraulic transmission has caught attention as an innovative technique. The seawater hydraulic system has the function of pressure self-compensation, which are often designed into an open-circuit system. Therefore, it is suitable for application in ocean engineering and deep underwater apparatus. Such apparatuses include manned deep-sea submersibles, unmanned underwater vehicles (UUVs), autonomous underwater vehicles (AUVs), underwater gliders, underwater tool systems, and so on (Liu et al., 2010; Isa et al., 2014; Yang et al., 2016). Seawater hydraulic axial piston pump (SWHAP) is a critical power component in underwater apparatus systems. It can be widely used in variable ballast systems to control the depth and attitude of the underwater apparatus (Zhang et al., 2013; Yang et al., 2015; Liu et al., 2015). The valve-port plate pair is one of the crucial frictional pairs in SWHAP, as most of the leakage, flow ripple, and frictional loss generated are through this frictional pair, which would result in a significant influence on the performance and reliability of SWHAP. Therefore, the reliability analysis for valve-port plate pair is essential to be considered during the development of SWHAP.

Although the seawater hydraulic transmission technology has developed rapidly, the research on the reliability of SWHAP is underreported. Due to the similarities between SWHAP and traditional oil axial piston pump, many research efforts discussed in this paper are based on the reliability analysis and design optimization of the traditional oil axial piston pump. Xu (1991) and Sun et al. (1992) established the wear probabilistic reliability analysis and design method for the oil axial piston pump by using the stress-strength interference model. An efficient layered clustering algorithm method to diagnose and predict the reliability of aero hydraulic pump has been formulated by Du et al. (2013). Zhang and Liu (2013) presented the reliability design and sensitivity analysis of critical components in the oil axial piston pump and hydraulic pressure pipeline systems based on the random moment of matrix method. The reliability applications in wear degradation and mechanism analysis, as well as the accelerated life test of the hydraulic pumps and valves, have also been reported (Yang et al., 2014; Ma et al., 2015; Daniel et al., 2015; Guo et al., 2016). However, these reliability analysis methods primarily are based on the probability theory, with the premise that the distribution law of the stress, material strength, and pv value of the frictional pairs are known (Hu and Du, 2012; Hu et al., 2013, 2014). It is believed that the material combinations in SWHAP such as stainless steel, and polyetheretherketone (PEEK) engineering plastic are different from the oil axial piston pump. The

* Corresponding author.
E-mail address: niesonglin@bjut.edu.cn (S. Nie).

https://doi.org/10.1016/j.oceaneng.2018.06.007
Received 7 December 2016; Received in revised form 1 May 2018; Accepted 4 June 2018

distribution information of the material combinations and working parameters in SWHAP are insufficient, and only the interval value of the mentioned design parameters can be obtained. It has been demonstrated that small deviation distribution parameters and their actual values may result in significant errors in the reliability analysis results (Ben-Haim and Elishakoff, 1990). Therefore, these probability reliability analysis methods for oil axial piston pump cannot be directly applied to the reliability of SWHAP without detailed distributions of the parameters, which may lead to the early failure of the pump.

To remedy the deficiencies of the traditional probabilistic method, and describe the parameter uncertainty when the deterministic information is inadequate, the non-probabilistic theory such as interval model and the convex model was proposed (Ben-Haim, 1993, 1994; Elishakoff and Elisseeff, 1994; Jiang et al., 2007). In the past two decades, many signs of progress have been made in non-probabilistic reliability analysis methodologies. Guo et al. (2001) and Li et al. (2013) developed some interval models to measure the non-probabilistic reliability index for uncertainty structural analysis. Similarly, a non-probabilistic reliability model which considered the dependency of the interval variables had been established by Xiao et al. (2013). Cao and Duan (2005) established a non-probabilistic reliability index to measure the safety of structures with both ellipsoidal models and interval parameters. Qiu (2003) provided a series of numerical algorithms of the non-probabilistic for static structural mechanics and dynamical problems. Topology optimization based on the multi-ellipsoid convex model and reliability analysis method based on a combination of probability and convex set models have been presented to deal with the grouped uncertainties (Luo et al., 2009a, 2009b). In recent studies, many innovations on the convex model have been made to improve its efficiency and accuracy. The recent developments include the work of Jiang and Han, where a correlation analysis technique is proposed (Jiang et al., 2011), as well as a general convex model coupled with several practical algorithms (Jiang et al., 2013). Besides, significant efforts have been reported regarding methods for time-variant and time-dependent reliability analyses (Jiang et al., 2014a; Zhang et al., 2017). Comparatively, the multidimensional parallelepiped model process was combined with the first-passage failure mechanism to make time-variant uncertainty analysis (Jiang et al., 2014b, 2015). More recently, Kang and Zhang (2016) presented a minimum-volume ellipsoidal convex model, with which one can improve the efficiency and enhance the confidence level of the non-probabilistic analysis.

Although extensive work has been conducted to study the non-probabilistic convex theory, some severe problems inevitably will be caused when one introduces the non-probabilistic reliability analysis techniques into the SWHAP problems. Firstly, the seawater hydraulic axial piston pump is still in the stage of small batch design and production, with limited available and uncertain information. Secondly, the distribution parameters of the uncertain variables, especially the distribution interval of stress, *pv* value (the product of the contact specific pressure and the linear velocity) and limiting [*pv*] value (It is the usual criterion to evaluate the critical operating conditions under which the material fails) of the valve-port plate pair in SWHAP have rarely been investigated. Thirdly, no evidence has been found in the development of a suitable non-probabilistic model to analyze the reliability of valve-port plate frictional pair in SWHAP. Therefore, it seems necessary to obtain the distribution interval of the uncertain variables of valve-port plate frictional pair according to the property analyses of the mechanics, and furthermore, to develop a useful non-probabilistic model for analyzing the reliability and optimizing the structure of valve-port plate frictional pair in SWHAP. The developed model will consider the uncertainties in the loading, rotational speed and material properties of the valve-port plate pair. The rest of this paper is organized as follows: in Section 2, the force of the valve-port plate pair is analyzed, and the uncertainty characteristics of the limiting [*pv*] value of the material combination is obtained by friction and wear test. Based on that, we establish a limit-state function using the stress-strength interference model. In Section 3, the non-probabilistic reliability analysis method for the valve-port plate pair is presented. Then the non-probabilistic reliability analysis, sensitivity analysis and design optimization of the valve-port plate pair is given in Section 4. Discussions and conclusions are provided in Sections 5 and 6, respectively.

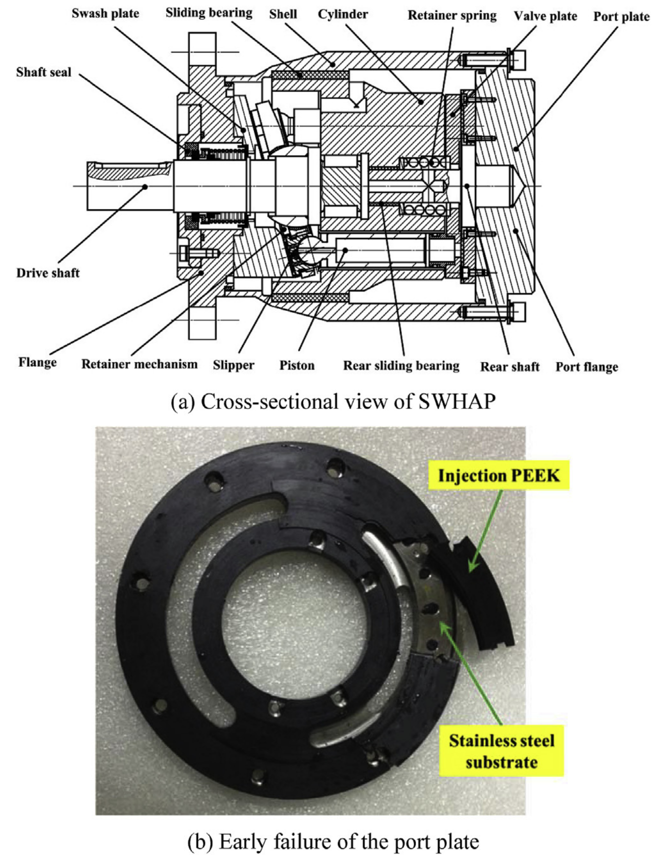

Fig. 1. Configurations of SWHAP and failure of the port plate.

2. Statement of the problem

In this section, the failure problem of valve-port plate pair in SWHAP is analyzed. And we present the mechanical analysis and friction and wear test to discuss the major factors that affect the reliability of the valve-port plate pair, and then develop a limit-state function for the non-probabilistic reliability analysis.

2.1. Failure mode of valve-port plate pair

Fig. 1 illustrates the configuration of the middle-pressure SWHAP that can work in a seawater environment. As shown in Fig. 1(a), the drive shaft drives the cylinder block and valve plate, and the sliding bearing supports the cylinder and drive shaft component. The valve-port plate pair is designed based on the principle of redundant squeezing force. Several screws fix the port plate which is sealed with the O ring, to avoid leakage in the port plate-port flange gap. The floating valve plate and the retainer spring could automatically compensate for the lubricating gap between the valve plate and port plate. The rear sliding bearing could balance the eccentric moment caused by the port plate. The material combinations of the pump such as AISI630 stainless steel and polyetheretherketone (PEEK) engineering plastic could resist wear and seawater corrosion. In our preliminary study, the safety factor and probabilistic reliability method based on hypothesis have been used to design the critical frictional pairs in SWHAP, which leads to early failure of the port plate after a one-hour performance test