Chinese Journal of Aeronautics, (2017), **xxx**(xx): xxx–xxx

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Erosion degradation characteristics of a linear electro-hydrostatic actuator under a high-frequency turbulent flow field

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Received 31 March 2017; revised 7 July 2017; accepted 19 September 2017

KEYWORDS

Computational fluid dynamics;
Degradation characteristics;
Dynamic contaminated particles concentration;
Erosion;
Linear Electro-Hydrostatic Actuator;
Performance degradation

Abstract The paper proposes a performance degradation analysis model based on dynamic erosion wear for a novel Linear Electro-Hydrostatic Actuator (LEHA). Rather than the traditional statistical methods based on degradation data, the method proposed in this paper firstly analyzes the dominant progressive failure mode of the LEHA based on the working principle and working conditions of the LEHA. The Computational Fluid Dynamics (CFD) method, combining the turbulent theory and the micro erosion principle, is used to establish an erosion model of the rectification mechanism. The erosion rates for different port openings, under a time-varying flow field, are obtained. The piecewise linearization method is applied to update the concentration of contaminated particles within the LEHA, in order to gain insight into the erosion degradation process at various stages of degradation. The main contribution of the proposed model is the application of the dynamic concentration of contamination particles in erosion analysis of Electro-Hydraulic Servo Valves (EHSVs), throttle valves, spool valves, and needle valves. The effects of system parameters and working conditions on component wear are analyzed by simulations. The results of the proposed model match the expected degradation process.

1. Introduction

Integrated Electro-Hydrostatic Actuators (EHAs) have seen increased application in More-Electric Aircraft (MEA), due to their numerous advantages including high reliability, long lifetime, and high efficiency.[1–4] Traditional power-integrated Rotary Electro-Hydrostatic Actuators (REHAs) are facing many problems, such as severe heating, big inertia, low-frequency response, and difficulty in redundancy configuration. In order to solve these deficiencies, many researchers have

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Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

https://doi.org/10.1016/j.cja.2017.12.002
1000-9361

proposed direct-drive EHAs.[5–9] Li et al. have presented a novel LEHA for the pump control system based on a collaborative rectification structure for linear pumps where the fundamental subsystem consists of two Direct Drive Pump Cells (DDPCs).[10] Their prototype has verified feasibility of the proposed actuator and flexibility of the dual-control strategy. Although the system has a number of advantages, its reliability characteristics, such as degradation and life prediction, need to be addressed and further improved. Applying the novel operating principle, the LEHA has improved these performance issues, but it has also introduced a problem due to the fact that it cannot integrate filters. The novel LEHA is also an integrated closed system which can increase the power-to-weight ratio. A linear resonance motor drives piston cylinder suction and discharges oil. The spool of a rectification slide valve is rigidly connected with the driving cylinder rod, resulting in the active rectification mechanism to be in a high-frequency condition. Due to non-filter design, contaminated particles will continuously cycle in an LEHA during its operation, which will precipitate further erosion and produce more contamination particles. Consequently, compared to a conventional hydraulic system with filters, the rectification mechanism in an LEHA can fail more rapidly, which can lead to a dominant progressive degradation process.

The rectification mechanism is commonly present in hydraulic systems, and when coupled with oil contamination, it can result in system failure. Some research results have indicated that contamination particles in oil wash out and wear the edges of valve components.[11] The resulting leakage increase caused by wear accounts for approximately 60% of cases of component failure. According to the research by Zhang et al., the wear resulting from particulate contaminants causes an increase in the internal leakage, the output current hysteresis and null leakage, the input current threshold, and the pressure gain, as well as a decrease in the gain linearity of the electrohydraulic servo valve.[12] The Physics-of-Failure (PoF) models of particle erosion wear introduced by Fang et al. show that the erosion wear has significant impacts on the electrohydraulic servo valve's service life and reliability.[13] Furthermore, the erosion of an LEHA is even more serious due to the particular type of motion and active rectification under relatively severe conditions. This paper is focused on the performance degradation of an LEHA induced by erosion wear.

Performance degradation analysis is extensively applied in numerous engineering fields to evaluate safety of machine parts and equipment.[14] The associated theories can be divided into three categories: (a) failure physics, (b) probability statistics, and (c) artificial intelligence. The first approach studies the structural integrity of an object with respect to operating conditions and mechanical and physical properties of materials used to make the object. Probability statistics models are mainly suitable for analysis of degradation based on stress fatigue, which requires significant amount of test data. Alternately, the artificial intelligence approach is dependent on field performance degradation data. In the field of durability analysis and life prediction, numerous physical experiments are performed in order to evaluate the life and reliability of hydraulic components. Therefore, during the design stage, it is essential to analyze the overall LEHA system based on the physical nature of erosion.

A significant number of studies have been performed to analyze the effect of erosion on system performance degradation. Fitch and Hong investigated the effects of contaminated oil on erosion in pumps and contaminant lock in servo valves, and proposed a new method to predict service life.[15] The occurrence of contaminant lock is accidental whereas the erosion caused by contaminant particulates is a continuous process which takes place as long as the system is operational. Vaughan et al. examined the effects of the particle size and concentration, differential pressure across the metering land, spool opening, spool surface, flow direction, as well as fluid characteristics on erosion wear.[16] Yang et al. adopted a gamma process to describe the internal structure degradation under erosion for electrohydraulic servo valves.[17] Zhang et al. presented a degradation assessment and life prediction method for electrohydraulic servo valves based on the CFD method and hydraulic simulation.[12] In addition, other researchers have predicted structural wear by CFD techniques.[18–20] The mechanism of erosion for a ductile metal material is a micro-cutting process, which was put forward by Finnie, who also presented an analytical erosion model to calculate erosion rates.[21] Tilly proposed that erosion of ductile materials could occur in two stages, where the first stage is micro-cutting whereas the second stage is surface fragmentation, and found that resulting estimates gave a good correlation with experimental data.[22] Recent theoretical and experimental studies explored the effects of particle properties, impacting speed and angle, and material properties on the severity of erosion. Among those studies, the Edwards model has been widely accepted to be applicable to erosion for gas-solid, liquid-solid, or gas-liquid-solid flow, where particle properties, impacting speed and angle, and material properties are taken into account.[23] Therefore, the Edwards model is utilized in this study because of its extensive applicability and high prediction accuracy. In addition, erosion due to the rectification mechanism in an LEHA under the influence of contaminant particles in hydraulic oil falls within the model framework.

This paper proposes a new method for analyzing performance degradation under dynamic erosion wear. The Edwards model is utilized to obtain erosion rates due to its broad applicability and high prediction accuracy. Furthermore, erosion rates of the rectification mechanism for different port openings and different degradation stages are estimated. In addition, in order to obtain the degradation curve under dynamic erosion wear, the concentration of contaminant particles is updated at different stages of degradation. Finally, the proposed degradation model is applied to simulate the wear degradation process in an LEHA under different flow conditions, and results are compared with results from traditional wear studies.

2. Problem description

2.1. Working principle of the LEHA

The schematic representation of the proposed LEHA architecture is shown in Fig. 1, whereas Fig. 2 represents the hydraulic circuit diagram and control loop of a traditional REHA. The REHA utilizes a motor and a pump to convert electrical energy to hydraulic energy, where the motor has reversible rotation in order to control the flow direction of hydraulic oil. Compared with the REHA, the proposed LEHA has the following distinct characteristics: (1) a linear resonance motor

Please cite this article in press as: LI Y et al. Erosion degradation characteristics of a linear electro-hydrostatic actuator under a high-frequency turbulent flow field, *Chin J Aeronaut* (2017), https://doi.org/10.1016/j.cja.2017.12.002