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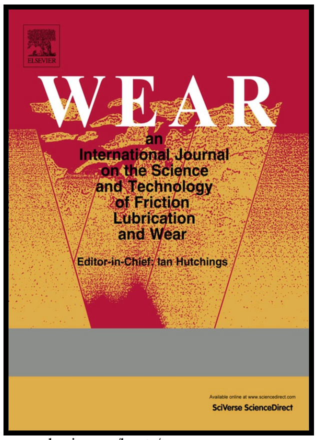

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Numerical Study of Solid Particle Erosion in Hydraulic Spool Valves

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Abstract: The null characteristics of hydraulic spool valves change significantly due to solid particle erosion. In the present work, a numerical model has been established to predict the material removal rate and the worn profile evolution with erosion in hydraulic spool valves. The particle trajectories are solved by a stochastic separated flow model based on eddy interaction, and the squeeze film is included as a part of a particle-wall interaction model. The erosion rates are then predicted by the particle impact characteristics, and the worn profiles are obtained by a time-discrete and spatial-discrete update method. The major influencing factors, including particle size, differential pressure, spool opening, and flow direction, are discussed. Through comparison with laboratory experiments and a field case, the model was verified. The present model and theoretical analysis are intended to elucidate the life-cycle management, life evaluation and degradation-resistant design of the spool valve.
Keywords: solid particle erosion, hydraulic spool valve, numerical study, erosion rate, worn profile, influence factors

1. Introduction

A spool valve is a type of principal control component in hydraulic systems and is always used as the power output stage of a servo valve (shown in Fig. 1), which is widely used in aviation, aerospace, ships, and other modern major equipment areas. In spool valves, the fluid flows between a pair of sharp edges, and the solid particles that are carried by the fluid impact the target surface with high velocity, leading to erosion wear. The metering edges become blunt and the spool lap and bushing decrease due to this solid particle erosion. As a result, the spool valve null region characteristics, which have an important influence on system operation and stability will be degraded. Thus, the prediction of erosion degradation process of a spool valve is important to the reliability evaluation and life-cycle performance prediction of a hydraulic servo system.

Solid particle erosion has always been a complicated problem in engineering, and research into erosion can be traced back to the construction of the Brooklyn Bridge in 1876 [1], where Roebling used a granite slab instead of metal as the reflector to improve the lifetime of the sand-suction equipment. H. Wahl and F. Hartslein [2] summarized the influence factors of erosion wear on the basis of engineering practice. By the mid-20th century, with the development of erosion wear theory and the turbulent particle dispersion model, the erosion prediction of various hydraulic and pneumatic components became possible, and the erosion in turbines [3][4], pump casings [5], pipes [6][7] and various valves [8][9] was studied theoretically. Most of the investigators have focused on the wear location and the initial erosion rate to obtain the erosion protection scheme, but the worn profile prediction has always been ignored. For a spool valve, the worn profile of metering edges must be considered, because the null behaviors are sensitive to the shape of the metering edge. In some theoretical studies [10], the shape of the worn metering edge has been simply assumed, without proof, to be a quarter-circle. However, the erosion experiments of spool valves by Vaughan [11] show a different worn profile and indicate that the erosion prediction may be incorrect under the quarter-circle assumption, the change of profile may in turn change the erosion rate. Thus, in addition to erosion rate, prediction of the worn profile is necessary.

The numerical studies of particle erosion are typically aided by commercial Computational Fluid Dynamics (CFD) software [4-9], but some achievements and complicated models are not included because of the lag in software development and the requirement to raise the calculation efficiency. For example, in Fluent, the squeeze film effect is not considered in the particle-wall interaction model. The squeeze film is the liquid layer that has a cushioning effect on approaching particles. Clark [12] made a quantitative analysis of the squeeze film in slurry erosion, and the results indicated that when the effect of the squeeze film is ignored, the calculated erosion rate value has a significant discrepancy with the experimental value, especially for small particles. Additionally, the anisotropy of turbulent fluctuation, the temporal correlation of turbulent eddies and the spatial correlation between the turbulent eddy and particle, which are important to particle dispersion calculation [13], are also absent.

In the present work, a particle erosion prediction model has been built to predict the erosion rates and worn profiles in a hydraulic spool valve. In the numerical model, the particle trajectories are solved by a stochastic separated flow model in which the temporal correlation of turbulent eddies and the spatial correlation between the turbulent eddy and particle are included, and a discussion on the influence of the correlations is also provided. The squeeze film is included as a part of the particle-wall interaction model. The erosion rates are then predicted by the particle impact characteristics, and the worn profiles are obtained by a time-discrete and spatial-discrete update method. Major influencing factors such as particle size,