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An Eccentric 3-D Fluid-Structure Interaction Model for Investigating the Effects of Rod Parallel Offset on Reciprocating-Seal Performance

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Abstract: The rod parallel offset ruins the axial symmetry of reciprocating seals, making the traditional 2-D model inappropriate for quantitative analysis. We propose an eccentric 3-D fluid-structure interaction (FSI) model, comprising the parallel-offset and mixed-lubrication sub-models to investigate the influence of parallel offset on the seal's micro- and macro- performance. Details of the sealing zone, friction and leakage features are analyzed for an O-ring seal at different eccentric distances, system pressures and velocities. Comparisons between the friction characteristics in the mixed-lubrication and dry conditions are also implemented in this paper.

Keywords: reciprocating seal, parallel offset, eccentric, fluid-structure interaction

1. Introduction

Reciprocating seals play a critical role for the efficiency and safety of hydraulic cylinders. One kind of misalignment for the cylinder is rod parallel offset, which is usually due to machining deviation or radial load. This offset causes stress concentration, and produces uneven contact pressure, leading to the friction varying along the circumferential direction and inducing the seal distortion.

In the past few years, related researches have been done on the effects of parallel offset. For radial lip seals, Tasora [1] calibrated a three-dimensional (3-D) finite-element model under radial loads to assess the constitutive model of the seal's material. For reciprocating seals, the influence of rod parallel offset on the flow rate of the seal gaps was discussed theoretically[2], with the assumption that there is one constant radial distance in the sealing zone and that both the rod and seal are rigid. Pinedo presented an analytical three-dimensional eccentric model of the rod lip seal to study the contact force distribution and researched the misalignment's effect on the dry friction [3], temperature distributions and wear progress[4], which are useful for learning how parallel offset affects seal performance. However, Pinedo's work focused primarily on the effects of parallel offset under dry condition, excluding the lubrication environment of the sealing zone.

In the reciprocating sealing zone, the frequent existence of mixed lubrication has been demonstrated by theoretical and experimental results [5-16]. The method combining finite-element analysis (FEA) software with the iterating numerical procedure was proposed to reveal the sealing zone's various characteristics. The transient effect [12, 17] and the impact of viscoelasticity of polymers [15] were discussed by this coupled method. This method also helped illustrate the effects of starved conditions [16] on the reciprocating seal performance. Because of the reciprocating seal's axial symmetry, all numerical models described above were simplified into a two-dimensional (2-D) model (i.e., a cross-section of the seal), and Peng et al. [18] verified its accuracy. However, when rod parallel offset occurs, it ruins the characteristics of axial symmetry and invalidates the 2-D model. To the best of our knowledge, there hasn't been a reliable method for studying the lubrication details of the sealing zone (film thickness, film pressure, etc.) under rod parallel-offset conditions.

This paper proposes an eccentric 3-D fluid-structure interaction (FSI) model to comprehensively investigate the effect of rod parallel offset on the reciprocating-seal performance. This model will give insight into the micro and macro characteristics of the misaligned reciprocating seal under different working conditions. Taking advantage of its symmetry, we analyze half of the reciprocating-rod seal. The model comprises two parts: the ***parallel-offset sub-model*** and the ***mixed-lubrication sub-model***, which are described in Section 2. Although the sealing performance of the O-ring may not be as good as that of other structure seals, e.g., the "U-cup" seal or the combined seal, the O-ring is still used in the dynamic sealing condition because of its simple structure and compact groove. The modeling of the O-ring isolates the seal structure's influence, and its simple structure makes repeat testing and verification easy. Therefore, an example of the O-ring seal at different parallel offsets is discussed in Sections 3 and 4.