Wear 311 (2014) 71–80

Contents lists available at ScienceDirect

Wear

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

A comprehensive model of wear, friction and contact temperature in radial shaft seals ☆

D. Frölich *, B. Magyar, B. Sauer

Institute of Machine Elements, Gears, and Transmissions (MEGT), University of Kaiserslautern-Gottlieb-Daimler-Straße 42, 67663 Kaiserslautern, Germany

ARTICLE INFO

Article history:
Received 3 September 2013
Received in revised form
26 December 2013
Accepted 31 December 2013
Available online 9 January 2014

Keywords:
Radial shaft seal ring
Contact temperature
Wear
Friction torque
Finite element simulation

ABSTRACT

Radial shaft seals are used in a variety of applications, where rotating shafts in steady housings have to be sealed. Typical examples are crankshafts, camshafts, differential gear or hydraulic pumps. In the operating state the elastomeric seal ring and the shaft are separated by a lubrication film of just a few micrometers. Due to shear strain and fluid friction the contact area is subject to a higher temperature than the rest of the seal ring. The stiffness of the elastomeric material is intensely influenced by this temperature and thus contact pressure, friction and wear also strongly depend on the contact temperature. In order to simulate the contact behavior of elastomer seal rings it is essential to use a comprehensive approach which takes into consideration the interaction of temperature, friction and wear. Based on this idea a macroscopic simulation model has been developed at the MEGT. It combines a finite element approach for the simulation of contact pressure at different wear states, a semi-analytical approach for the calculation of contact temperature and an empirical approach for the calculation of friction. In this paper the model setup is presented, as well as simulation and experimental results.

1. Introduction

The field of applications for elastomeric radial shaft seals is wide and diverse. Automotive industry, washing machines, water pumps or wind power plants are just four examples that emphasize how fundamentally different the applications and thus the requirements for seals can be. A typical radial shaft seal design is illustrated in Fig. 1.

In some applications, temperature is the critical factor. Especially where large diameters and circumferential speeds are involved, the thermal properties of the elastomer need to be taken into consideration. In other applications, the degree of efficiency and the reduction of friction are significant. In all fields of use, the seal rings need to outlast the lifetime of the machine they are installed in. Thus ageing and wear must be reduced to a minimum. Due to this variety of applications and requirements, the choice of an appropriate seal ring design and material is a challenge.

During the development process of new seal designs or new elastomer materials, test rigs are generally used to check the seal ring under conditions that are close to the designated field of use. Experiments focusing on wear are especially time consuming. This is the reason why in recent years, simulation models have been increasingly used for preliminary tests of the seal ring behavior and to reduce the experimental expense.

In a first section, this paper will give an overview of different simulation models for radial shaft seal rings that have been developed in companies or research institutes in recent years. Then the model that has been developed at the Institute of Machine Elements, Gears and Transmissions (MEGT) will be explained. The structure of the model is introduced and a comparison with experimental results is given.

2. State of the art

Many researchers have developed simulation models to investigate the behavior of seal rings in detail. Basically it can be distinguished between macroscale and microscale modelling approaches. The models making use of microscale approaches typically focus on a small section of the seal system that is modelled physically detailed and very close to reality. These models can be used to extend the fundamental understanding of the functionality of radial shaft seal rings. Macroscale models are often based on simplified empirical approaches, combined with higher scale physical models. The focus of these macroscale models is on the function of the overall system.

Below the state of the art of these seal ring models is presented.

Most of the macroscale models focus on just one aspect, that is, on temperature, friction, or wear. By the use of an electro-thermal analogy-model Upper [1] is able to determine the contact temperature in a seal ring as well as the temperature distribution. It can be shown that the wear of a seal ring and the associated

☆ This paper was presented at the 2013 World Tribology Congress.

* Corresponding author. Tel.: +49 631 205 3715.
E-mail address: daniel.froelich@mv.uni-kl.de (D. Frölich).

0043-1648/$ - see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.wear.2013.12.030

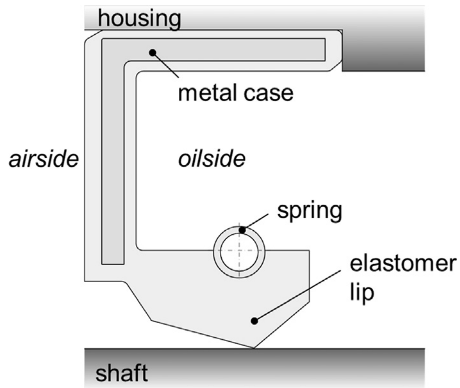

Fig. 1. Schematic of radial shaft seal ring components.

growing contact width have a significant influence on the temperature distribution within the seal ring. A high temperature gradient within the seal ring volume is detected. Based on these scientific findings, first finite element models that combine thermal and mechanical load steps are developed.

Stakenborg and Ostayen investigate the temperature-distribution in the contact zone of radial shaft seal rings [2] with the finite element method and a thermal network. The authors demonstrate that the larger proportion of the heat generated in the contact area dissipates through the shaft and a considerably smaller proportion dissipates through the seal ring.

Kang and Sadeghi use a microscale model to simulate the temperature-distribution in the contact zone of seal rings [3]. Making use of the elasto-hydrodynamic theory, they find that the contact temperature on the surface of the seal ring is higher than the temperature on the shaft surface.

In [4], the temperature distribution due to friction heat in a radial shaft seal ring is simulated. The associated thermal deformation due to the friction power generated in the contact zone is studied. It can be found that the influence of thermal deformation on the width of the contact zone and the resulting contact pressure is small. The elastomeric behavior is modelled using constant Mooney–Rivlin coefficients, independent of the current temperature distribution. In [5] and [6], the temperature distribution within a radial shaft seal ring is calculated. The authors conclude that the simulation of the friction torque in seal rings requires a combined thermal and mechanical model. First, the temperature distribution is determined and then the mechanical behavior of the elastomeric material, taking into account its temperature dependency, is simulated. Thereby, the contact pressure and the friction between seal and shaft can be simulated more accurately. A detailed insight in the contact temperature of seal rings is given in [7]. A conjugated heat transfer simulation is conducted in order to study the influence of the contact friction, oil sump temperature and surrounding elements, e.g., shaft and housing on the contact temperature. The comparison with experimental results using a thermographic camera shows a good accordance. An empirical approach to the temperature dependence of radial shaft seal friction is presented in [8]. Through the analysis of test rig results a correlation of friction energy and contact temperature is deduced. In an iterative calculation, both dimensions can be determined. Dry friction and fluid friction make up the resulting overall friction.

At the same time, the simulation of wear in seal rings is investigated. In [9], a finite element model for the simulation of wear in a reciprocating elastomeric seal ring under different load conditions is published. The occurring wear is modelled in the form of node-displacements of the finite element mesh. The effect of wear on the resulting pressure distribution can be analyzed. Node displacement is the first of three common possibilities of modelling wear in FE-models. This strategy has been adopted in later works of other authors. In [10], wear of radial shaft seal rings and PTFE lip seals is simulated using a similar FE-approach in the software ANSYS. The wear is not applied as a node displacement, but by deactivating elements. This method is called element-death and represents the second basic possibility of modelling wear. One advantage is that using this strategy a contortion of the mesh is avoided. With element death, a continuous wear progress cannot be modelled. The accuracy is limited by the element size in the contact zone. This can be regarded as a disadvantage. The software ABAQUS offers a FORTRAN-Subroutine “umeshmotion” that can be used to move mesh-nodes independent of the underlying material in an adaptive mesh region. This subroutine is used by [11] to model wear in a pin-on-disc tribometer. The authors compare experimental tribometer results with simulation results, using Archard's wear equation and find that the accuracy of this modelling strategy is acceptable. A third possible modelling strategy of wear in a FE-analysis is used by [12]. In this work, the seal is modelled as an axisymmetric component using the software MSC.MARC. The application of wear is not accomplished through mesh-modifications, but for each wear state, the geometry, described by contour points along the contact zone, is updated. The current geometry is then meshed and used for further simulation steps. This strategy is particularly powerful for wear amounts larger than the elements in the FE-mesh.

The first microscale models for the simulation of the tribological behavior of radial shaft seal rings have been developed approximately 25 years ago. In 1989, Gabelli develops a model for the simulation of the lubrication film thickness [13]. In his model, the film thickness formation combines micro-EHD action, based on interactions of surface asperities and hydrodynamic action at the sealing interface, based on the solution of the general Reynolds' equation. The surface roughness of seal and shaft is described with microundulations. Salant develops a simulation method for the estimation of the leakage rate [14], based on the solution of the general Reynolds' equation, and taking into consideration the distortion of the seal surface undulations during operation, as described by [15]. In regions, where the local pressure falls below the cavitation pressure, the existence of both, liquid and gas are taken into consideration. This simulation model is continuously refined and developed further by Salant. Other scientists have taken up this simulation method in their own simulation models. Van Bavle et al. analyze different seal layouts based on the simulation method developed by Salant [16]. Their description of the lubrication film is used in later research by other scientists. In [17], the influence of the oil meniscus on the lip seal behavior is simulated, demonstrating, that asperity contact occurs in the seal interface if the meniscus moves too far to the liquid side. In [18], an extension of the model shown in [14] is presented. It can be applied for mixed lubrication, taking into consideration micro-cavitation and micro-deformation of the surface undulations of the seal lip. With the simulation method presented in [19], the fluid mechanics of the lubrication film and the elastic lip deformation are solved using the Reynolds' equation with flow factors. This statistical approach improves the computational efficiency. This approach is extended by [20], where the deformation of the seal lip asperities is modelled, using a matrix of elasticities that are predetermined with FE-simulations. In [21], a thermal EHL-model of a seal ring is presented. The deformation is also taken into account by using a matrix of elasticies. An artificial surface is used to take into consideration the surface asperities. The system of equations is solved with the FE-method, instead of the wide spread finite difference method.

The above listed literature illustrates the difference between the macroscale and microscale simulation approaches. In recent