Dynamic Simulations of Radial Lip Seals Followability in an Industrial Gearbox

This unique modeling capability will allow selecting or developing the shaft seals that would meet and exceed modern gearbox demanding application.

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INDUSTRIAL GEAR UNITS ARE WIDELY USED IN POWER TRANSMISSION SYSTEMS. THEY ARE COMPOSED OF SHAFTS, GEARS, ROLLING ELEMENTS BEARINGS AND DYNAMIC LIP SEALS. THE SEAL’S PERFORMANCE IS CRITICAL FOR A PROPER FUNCTIONING OF THE SYSTEM.

Water or contamination ingress into a mechanical system may lead to a premature failure. Leakage of oil may have the same effect and be harmful for the environment. Depending on the application, seals may need to operate under various dynamic conditions, such as wide range of rotational speed (RPM) and temperatures, Shaft to Bore Misalignment (STBM), shaft Dynamic Runout (DRO) or global structure deformations.

The prediction of dynamic seal performance is a complex task. The rotating lip seals are usually made from elastomeric materials that display both, hyperelastic and viscoelastic behaviors. Combined with the dynamic operating conditions, the simulation of seal performance requires time dependent approaches that are very often time consuming. Innovative modeling methods need to be developed in order to be usable by the development engineering community.

SKF has a novel approach to predict seal dynamic performance under dynamic conditions. A formulation of viscoelastic super elements is developed to predict the deformations of the seal lips. It is combined with a contact solver to assess contact force and its distribution around the shaft and other lip counter surfaces (such as other radial or axial locations). In order to demonstrate the functionalities and the advantages of the developed method, please consider an example of radial lip shaft seal shown in Figure 1. The problem addresses prediction of seal performance at cold temperature, large STBM and DRO conditions. Different material and spring options are assessed in order to improve the performance.

This unique modeling capability allows selecting or developing the shaft seals which would meet and exceed demanding modern gearbox applications. It also enables gearbox manufacturers to bring to the market more reliable gearboxes with improved performance.

**WHY DYNAMIC SIMULATIONS?**

**Current modeling methods**

Virtual evaluations of mechanical system performance today are very common in the design process. The risk of failing first prototypes during laboratory or field testing is significantly reduced as a result of extensive numerical analyses performed during product development and prototyping phases. In addition, the overall time to market may become shorter.

The most commonly used method is Finite Element Analysis (FEA). The body of a mechanical part, such as a seal, is discretized into finite elements. These elements contain equations describing the relation between strain and stress in the material and the mechanical behavior of the materials. For rubber seals this is important because the material exhibits incompressible hyperelastic behavior, as explained in [1,5,6].

In the first phase of the analysis, after the seal is designed using SKF internal engineering standards with consideration of application requirements, the virtual mounting of the seal is performed using quasi static simulation to verify if the designed product has actually met the specific engineering requirements. SKF has developed proprietary software, SKF Seal Designer, which is capable of conducting these types of simulations. The analysis allows engineers to determine (among other parameters) the following:

- seal deformation
- seal contact load
- contact pressure between the shaft and the seal, and between the housing and the seal
- stress and strain levels in various components, such as elastomeric material

Figure 1 displays an example of such analysis, with one of the SKF standard line seals installed in the housing and on the shaft. The deformations in the material and the contact loads are displayed.

The quasi static analysis is the first step in the design of a seal. It allows development engineers to asses seal retention in the housing, the level of contact load and pressure distribution profile to ensure proper sealing ability or, the strain and deformation to ensure seal integrity. Additionally, this method allows the seal design to be modified until the required levels of expected outputs are achieved.

**Getting closer to the real world**

The seal operating in application is by definition subjected to dynamic conditions. The shafts of gear units operate at various rotating speeds and due to the design and the stiffness of the different elements of the system, the seal may experience different effects like:

- (STBM), where the shaft centerline has a constant offset with the centerline of the seal housing
- (DRO), where the actual centerline of
the shaft is rotating around its theoretical centerline, which typically happens due to lobing and other shaft inaccuracies, as well as to the dynamic effects such as shaft flexing or vibration resulting from dynamic loads.

Figure 2 illustrates the effects of some DRO on the seal. The main risk is to lose contact between shaft and seal due to a very high DRO or rotational speed for a given seal design and material. This can lead to leakage from the mechanical system or ingress of water or contaminant into the mechanical system. The quasi static FEA is unable to predict this type of effect.

Operating temperatures can also widely vary in different applications. In some cases a low temperature start-up is required. This is especially important since material properties of rubber change dramatically with temperature.

ELASTOMERIC MATERIALS:

General overview

Rotating lip seals are usually made of elastomeric materials or rubber. These materials display high flexibility and elasticity as well as the ability to stretch by more than hundred percent and recover almost immediately to its original shape when used in the appropriate range of temperatures. In addition, they also have a viscoelastic nature, i.e., they dissipate energy, when they are deformed.

An elastomeric material or compound is composed of a polymer network, a filler network, plasticizers and numerous additives.

Figure 2: Schematic representation of a seal under DRO conditions.

Figure 3: Shear modulus as a function of temperature (left) and deformation frequency (right).

Figure 4: Multi-branch Zener viscoelastic model.
Typical elastomers, used for industrial gear units are:

- NBR (Nitrile butadiene rubber) with upper operating temperature limit of about 100°C;
- HNBR (Hydrogenated nitrile butadiene rubber) with a upper operating temperature limit of about 150°C;
- FKM (Fluoroelastomer) with upper operating temperature limit of about 220°C.

The filler network ensures good mechanical properties of the compound. The plasticizers and additives improve other properties like thermal resistance, chemical resistance to fluids, wear resistance or frictional performance. For extreme conditions or very aggressive lubricants, it is always possible to formulate and develop new compounds with specific properties.

While the high end utilization temperature limit of a compound is mainly determined by a chemically driven degradation process, the behavior towards low temperatures is more related to a mechanically reversible process. The elasticity of the compound is determined by the ability of molecular chains to move and adjust their conformations. This process is energy driven and is dependent on the temperature and rate of deformation. When the temperature decreases to a value closer to the glass transition temperature, the movements of the molecular chains become more limited; i.e. the material is “frozen” and the modulus of the material increases dramatically. The glass transition temperature $T_g$ is dependent on the deformation rate of the compound. Therefore specific material models are needed to cope with the dynamic behavior of elastomeric compounds. Figure 3 illustrates how the elastomeric compound properties change with temperature and frequency. Here you can see how the shear modulus of the material is changing based on variation of temperature and frequency.

**MATERIAL MODELING**

Several models exist to show the viscoelastic behavior of elastomeric materials [2]. They are all composed by an arrangement of springs and dashpots. In this work a multi-branch Zener model is used. It is shown in Figure 4.

A single branch is a combination of spring and a Voigt element [2], and the stress–strain relation reads:

$$\left\{ \begin{array}{l} \frac{1}{E_1} \sigma_1 + \lambda_1 \frac{d\sigma_1}{dt} = E_1 \left( \varepsilon + \lambda_1 \frac{d\varepsilon}{dt} \right) \\ \end{array} \right.$$

where

- $\varepsilon$ is the deformation;
- $\sigma_1$ is the stress in the branch;
- $\lambda_1$ is the relaxation time and $E_1$ and $E_2$ the modulus of the springs in this given branch of the Zener model.

The time dependency of the relation between the strain and stress for a viscoelastic material is clearly expressed in this equation. The integration of this formula for all the branches of the model gives the shear storage modulus $G'$, the shear loss modulus $G''$ and the value of $\tan \delta = G''/G'$ for a chosen reference temperature $T_{REF}$.

In order to model the behavior of the materials for any frequency of deformation and temperature, the Time-Temperature Super-Position (TTS) is used. The TTS principle implies that the same variation in a viscoelastic response obtained by changing the temperature can be also achieved by varying the frequency. In practice, it means that if $G'$ is the shear storage modulus at a frequency $\omega_1$, it can be expressed as a function of $G'$ at the reference temperature $T_{REF}$.

$$G'(\omega_1 T) = G'(\omega_1 T_{REF}) a_{T(T)}$$

where

$a_{T(T)}$ is the shift factor or TTS function value. The most used formula has been proposed by William, Landel and Ferry [3].

**DYNAMIC MODELING OF RADIAL LIP SEALS**

The computation of the deformation of sealing lip under dynamic condition(s) is based on the viscoelastic material relation (1). Special super-elements describing the relation between stresses and deformations in the seal structure are formulated. They have been used in the example below for discretization of the sealing lip with cross-section shown on Figure 5.

An interactive process is needed to solve the equations for all points in the seal cross section and around the circumference. The calculation for a given step includes both, an elastic term and a history term representing the viscoelastic effects [4]. For example, for the moment equilibrium for an element at a given time step the equation reads:
The computational algorithm for seal deformations is combined with a contact solver. It is indeed necessary to determine at the same time the deformation of the seal and the contact conditions between the seal and the shaft. The outputs are contact load distribution and area around the shaft circumference.

\[ \log (a_T(T)) = \frac{-C_1(T - T_{REF})}{C_2 + (T - T_{REF})} \]  \hspace{1cm} (3)

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**APPLICATION OF THE DYNAMIC MODELING TECHNIQUES**

**Presentation of considered cases**

For demonstration purposes of the capabilities and interest of the developed method, a radial shaft seal for a 50 mm shaft is used. Two different material options are used:

- Compound A with a \( T_g \) of -15°C
- Compound B with a \( T_g \) of -30°C

The material properties of these two compounds are presented in Figure 6. The figure includes the material shear modulus and \( \tan \delta \). \( \tan \delta \) is a good representation of the loss of energy during the deformation of the material and is the highest during the transition between the rubbery and glassy regions. Here compound A and B have globally the same behavior and the same shape of the curve of \( \tan \delta \). The difference between the compounds is that the transition between the rubbery and glassy states happens at lower temperatures: the curves for \( G' \) and \( \tan \delta \) are shifted to the left on the graphs. Compound B remains flexible until much lower temperatures are reached.

The following dynamic boundary conditions are considered:

- STBM : 0.2 mm TIR (Total Indicated Runout)
- DRO : 0.1 mm TIR
- Shaft speed: 4000 rpm, representing a surface speed of 10.5 m/s
Seal performance at ambient operating temperature:
The first step of the simulation is the installation of the seal on the shaft. This is shown in Figure 7. In this graph, the original seal shape is displayed in yellow. The deformed seal lip is shown in red. The dynamic simulation is then performed with the boundary conditions defined in section 5.1 at ambient operating temperature. The simulation provides the radial lip force around the circumference and the contact patch on the shaft around the circumference.

Compound A and B are compared in Figures 8 and 9. The results are very similar. The contact load has a similar level and displays a sinusoidal shape due to misalignment. The contact patch is continuous around the circumference. Due to the misalignment and DRO, the contact patch on the shaft has a wavy shape. The seal works perfectly in that condition with both compounds.
Seal performance at low temperatures:
The same simulations are performed at -10°C. Figure 10 shows the results for compound A and Figure 11 for compound B. For this temperature and dynamic conditions with compound A, the contact load and the contact patch are no longer continuous along the circumference of the shaft. This means that there is a gap between the seal and the shaft in this part of the circumference. Such a gap is not suitable because it can allow a leakage of lubricant. This gap is eliminated by replacing the seal material by compound B. The contact load becomes similar to the ambient simulation situation and the contact patch is continuous. This seal works well at that temperature. The results also show that the glass transition temperature $T_g$ is not enough to define the low temperature limit of a compound. The dynamic conditions under which the seal operates are extremely important.

PERFORMANCE AT EXTREME SPEED AND LOW TEMPERATURE.
As a last example, the simulation is done with compound B at -10°C at extremely high rotational speed (20000 rpm, i.e. 50 m/s). The results are shown in Figure 12. In this case the contact load and the contact patch are not continuous along the circumference at that speed. Indeed, the glass transition of an elastomer, and therefore seal performance is dependent on its deformation rate. This illustrates that the model takes into account the Time-Temperature Super-Position TTS(TTS) principle. It is fully adequate for the determination of the performance at any temperature or rotational speed of the shaft.

GENERAL CONCLUSION
Rotating lip seal performance is commonly predicted by quasi static finite element methods. The available tools allow determination of the contact forces, stresses and deformations of the seal. However this is not enough to understand the behavior of a seal in application because of:

- the dynamic conditions applied to the seal (like DRO and STBM)
- the mechanical behavior of viscoelastic materials used for seals

For an accurate prediction of seal performance under dynamic conditions and at various temperatures, SKF has developed a new advanced simulation method. The method includes a viscoelastic material model, a contact algorithm and a special formulation of the elements describing the seal lip. The method allows very fast simulations compared to the full finite element analysis in dynamic conditions.

The presented study of seal performance under dynamic conditions shows that inappropriate material choice can lead to followability problems, at low temperatures or extremely high speed conditions. It also shows that quasi static simulations are definitively not sufficient. The method allows SKF to conduct simulations under real application conditions and helps to avoid numerous design loops during product development process. It can also help explain and resolve problems seen in a field. As a result, SKF can customize their seal designs and materials to better meet challenging customer requirements in real operating conditions.

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