Remarks on modeling the flexible seal ring housing

C Kundera¹, V Martsynkovskyy², A Zahorulko²

¹ Kielce University of Technology, Faculty of Mechatronics and Machinery Design, Al. 1000-lecia PP 7, 25-314 Kielce, Poland
² Sumy State University, Department of General Mechanics and Machine Dynamics, R-Korsakova 2, 40007 Sumy, Ukraine

E-mail: kundera@tu.kielce.pl

Abstract. When formulating models of dynamic face seals, two issues are of essential importance. The first concerns the determination of the forces formed in the medium film in the gap formed by the faces of two rings, while the second refers to the model of the flexible housing of one of the seal rings. The first issue includes the analysis of the medium flow through a narrow slit, taking thermal phenomena and deformations of slit-forming surfaces into account. The second issue concerns the modeling of properties of seal structural components, especially the modeling of elastic-damping properties of the flexible seal ring housing. This paper presents the results of simple relaxation tests of elastomeric rings and the procedure for analyzing these results and evaluating the elastic-damping properties of the rings tested. Finally, experimental results will be compared with theory.

1. Introduction

A number of theoretical and experimental works on the dynamics of seals, especially face non-contact seals, e.g. [1-6] have been published in recent years. Their review shows that dynamic properties of seals can have a significant impact on the dynamics of the whole rotor machine of a pump type, compressor. When formulating models of dynamic face seals, two issues are of essential importance. The first concerns the determination of the forces formed in the medium film in the gap formed by the faces of two rings, while the second refers to the model of the flexible housing of one of the seal rings. The first issue includes the analysis of the medium flow through a narrow slit, taking thermal phenomena and deformations of slit-forming surfaces into account. The problem is complex and still relevant, both in analytical solutions and in experimental research. The second issue concerns the modeling of properties of seal structural components, especially the modeling of elastic-damping properties of the flexible seal ring housing.

In many works with the analysis of the dynamics of face seals, the Kelvin-Voita (K-V) model [1-3] is most often used to describe elastic-damping properties of a flexible housing. Adopting the K-V model greatly simplifies the formulation of equations on the motion of a flexibly attached ring, and, then, the performance of the dynamic analysis of the system composed of a seal and a machine shaft.

Mechanical properties of elastomeric rings of the circular cross-section, the so called "O-rings", have been the subject of works not only on face seals, but also on plain bearings, pneumatic and hydraulic cylinders. The characteristics determining these properties are generally nonlinear and depend on deformation and deformation rates. They are made of polymer, gum-like and other materials.
This paper was motivated by works containing more complex rheological models used to describe properties of viscoelastic dampers, such as [7] and the properties of a gas film, for example, in a gas thrust bearing [8], using a model in the dynamic analysis [9]. Considering the theoretical models described in the above-mentioned papers, this paper presents the results of simple relaxation tests of elastomeric rings and the procedure for analyzing these results and evaluating the elastic-damping properties of the rings tested.

2. Presentation of the problem
The present analysis focuses on the flexible housing of a seal ring in the mechanical face seal. Figure 1 shows an example of the classic design of a face seal with a flexibly attached ring and, additionally, rotating together with the shaft of the machine i.e. the pump. The seal ring flexibly attached can be axially and angularly displaced relative to its transverse inertia axes.

![Diagram of the face seal design](image)

Figure 1. Diagram of the face seal design:
1- seal ring flexibly attached; 2- seal ring, stationary; 3,4- elastomeric O-rings; 5- spring, 6-cover; 7- pump packing; 8- shaft.

The elastomeric ring and different types of bellows (Figure 2) fulfill the function of a secondary seal in the flexible seal housing. Elastic bellows also act as a compression spring, and can be made of elastomeric material, Teflon, and thin stainless steel with good elastic properties and resistance to corrosion. All connections in bellows secondary seals are inseparable.

![Diagram of secondary seals with elastic bellows](image)

Figure 2. Diagram of secondary seals with elastic bellows:
(a) elastomeric bellow; (b) PTFE bellow; (c), (d) metal bellows.

Secondary seals play an important role in the reliable operation of the entire face seal. Therefore, their elastic-damping properties and friction force at the contact surface, e.g. with the shaft of the machine, should be considered in design calculations and, in particular, in dynamic analyses.

The frictional force on the secondary seal depends on its design (shape, mounting), load system (pre-clamp), lubrication conditions of contact with the seal surface. At the contact of the ring with the shaft, a friction force which, depending on the direction of the displacement, increases or decreases the pressing force of the elastic element, appears when axial displacements of the seal ring are involved. Thus, the friction force in the secondary seal can have a significant effect on the balance of forces acting on the main seal ring and determine the tightness. Under dynamic conditions, especially at the low amplitude of vibrations of the ring flexibly attached, the elastomeric ring will only be subject to internal deformations that depend on its material properties.

3. Identification of the properties of elastomeric rings
Different rheological models are used to describe elastic-damping properties of elastomeric rings, and their parameters must be experimentally determined. Such experiments are generally very complex, because they must take not only deformations, but also deformation rates at different times into account. These determinants (circumstances) make us try to simplify both the deformation model itself and the experiment leading to the determination of its parameters.
In the earlier work [10] an experiment was carried out on the "Ispect mini" strength machine using the appropriately designed construction of the elastomeric ring (Figure 3). The construction used is characteristic for the O-ring working in the conditions of the dynamic reciprocating motion load, e.g. in the face seal or servomotor.

During the experiments, the following actions of the load force were used to determine the relaxation characteristics:
- Force increment at 1 mm/s until the desired displacement value is reached, e.g. 0.5 mm;
- Maintenance of the set displacement value for a specified period of time during the simultaneous recording of the decrease in the load value due to the relaxation of the O-ring material. The maintenance time of the set displacement value was between 90 and 300 s.

The above-mentioned test procedure was carried out for elastomeric rings of dimensions: \( d = 3.5 \) mm, \( D = 54.5 \) mm, made of nitrile mixture (NBR). An example of the ring load change graph obtained directly from the computer controlling the test machine is shown in Figure 4.

The course of the load force change (relaxation force) describes the properties of the material the test ring was made of. By dividing the load force \( F(t) \) by the set value of displacement \( x_0 \) we obtain the characteristics of the replacement coefficient of elasticity \( K_{rel} \), often referred to as the coefficient of relaxation stiffness or the relaxation function. Figure 5 shows the characteristics of the replacement coefficient of elasticity \( K_{rel} \) corresponding to the course of the relaxation force shown in Figure 4.
Considering the results obtained from the experiment (Figure 5), the replacement coefficient of elasticity (the relaxation stiffness) can be approximated by the three-parameter function:

\[ K_{rel}(t) = K_o + K_1 e^{-\alpha t} \]  

(1)

where:

- \( K_o, K_1, \alpha \) – parameters obtained by approximation of the experimental characteristics.

Considering Figure 5, it can be seen that the approximation of experimental data with a three-parameter function is not very accurate. It can be improved by using the relaxation function with more parameters.

In the studies of photopolymers described in the above-mentioned paper [10], to approximate the results of the experimental tests, a five-parameter relaxation function was adopted in the form of:

\[ K_{rel}(t) = K_o + K_1 e^{-\alpha_1} + K_2 e^{-\alpha_2} \]  

(2)

The relaxation function assumed corresponds to the rheological model (Figure 6) consisting of two Maxwell models connected in parallel with the Hooke model.

If we adopt the five-parameter relaxation function to fit the above-presented experimental results (Figure 5), then we obtain very good accuracy, which shows the value of the \( R^2 \) test (Figure 7).
The evaluation of the elastic-damping properties of the system, in our case of a flexible ring housing, can also be carried out in the frequency domain (or the Laplace domain).

The force-displacement relationship can be expressed in analogy to the stress-strain constitutive law for a viscoelastic material:

\[ P(t) = \int_0^t K_{red}(\theta) \dot{x}(t-\theta) d\theta \]  

where: \( K_{red}(t) \) – function of relaxation (relaxation stiffness).

After the Fourier transformation of the constitutive equation (3), we obtain:

\[ F_p(j\omega) = j\omega F_{Krel}(j\omega) F_p(j\omega) \]  

The frequency dependent complex impedance is:

\[ H(j\omega) = j\omega F_{Krel}(j\omega) \]  

where: \( F_{Krel}(t) \) – transform of the relaxation function.

For the relaxation function in the form (1), its transform is respectively:

\[ F_{Krel}(j\omega) = \frac{K_o}{j\omega} + \frac{K_1}{\alpha_i + j\omega} \]  

and the frequency dependent complex impedance (5) takes the following form:

\[ H(j\omega) = K_o + K_1 \frac{j\omega}{\alpha_i + j\omega} \]  

The real part of the complex impedance (7) determines the elastic properties of the system, while the imaginary part divided by \( \omega \) - damping properties of the system.

\[ K(\omega) = H^{re}(\omega) = K_o + K_1 \frac{\omega^2}{\alpha_i^2 + \omega^2} \]  

\[ D(\omega) = \frac{H^{im}(\omega)}{\omega} = K_1 \frac{\alpha_i \omega}{\alpha_i^2 + \omega^2} \]  

If we take the five-parameter relaxation function (2) then the complex impedance and its real and imaginary parts take the following form:

\[ H(j\omega) = K_o + K_1 \frac{j\omega}{\alpha_i + j\omega} + K_2 \frac{j\omega}{\alpha_i^2 + \omega^2} \]  

\[ K(\omega) = H^{re}(\omega) = K_o + K_1 \frac{\omega^2}{\alpha_i^2 + \omega^2} + K_2 \frac{\omega^2}{\alpha_i^2 + \omega^2} \]  

\[ D(\omega) = \frac{H^{im}(\omega)}{\omega} = K_1 \frac{\alpha_i \omega}{\alpha_i^2 + \omega^2} + K_2 \frac{\alpha_i \omega}{\alpha_i^2 + \omega^2} \]  

The experimental test of determining the relaxation functions (1), (3) was performed at the axial load (Figure 3), hence we obtain the elasticity and the axial damping of the system, depending on the frequency.

The stiffness \( K(\omega) \) and damping \( D(\omega) \) characterize the linear reaction of the-force to the small sinusoidal seal ring (or shaft) displacement about equilibrium and to the corresponding velocity, respectively. The stiffness and damping together make up the complex frequency response (stiffness).
\[ G(j\omega) = K(\omega) + j\omega D(\omega) \] (13)

The real part of the frequency response is also called the storage modulus, and the imaginary part is called the loss modulus. After inserting values of the relaxation function parameters, i.e. \( K_0, K_1, K_2, \alpha_1, \alpha_2 \), experimentally determined (in the above-described experimental or relaxation tests) into the relationship (7-12), we obtain fully defined characteristics of the elasticity and damping of the flexible housing shown in Figure 3. Figs 8 and 9 show the characteristics of elasticity (8, 11) and damping (9, 12) of the flexible ring housing as a function of the frequency of induction.

Figure 8. Elasticity characteristics of the flexible housing for two rheological models: 1-three-parameter and 2-five-parameter.

Figure 9. Damping characteristics of the flexible housing for rheological models: 1-three-parameter and 2-five-parameter.

Considering the characteristics obtained, it can be seen that with the increase of the induction frequency, the elasticity of the flexible housing increases and the damping properties decrease to the fixed (stabilized) values.

Comparing the two relaxation approximation models assumed shows that for a five-parameter model, higher values of elasticity and damping coefficients are obtained for a fixed induction frequency.

In the range of low induction frequencies, the flexible housing is characterized by low elasticity but high damping properties. Such characteristics of the flexible housing can be important in the analysis of the dynamics of mechanical face seals, the so-called “low-speed”.

The above-mentioned description of the elastic-damping properties of the flexible housing has been carried out in the frequency domain. The dependencies determined can be directly used in a further analysis of the dynamics of a mechanical face seal, but also performed in the frequency domain. In addition, it should be borne in mind that the elastic-damping properties of a flexible housing depend on its design and the material of which the elastomeric ring was made. A relaxation test should be
performed and the appropriate parameters of the relaxation function should be determined for another design of the housing and another elastomeric ring material.

4. Conclusions
The procedure for identifying elastic-damping properties of a flexible housing of the seal ring in a mechanical face seal described in this article includes simple experimental relaxation tests and an analysis of their results in the frequency domain. The five-parameter relaxation model of the relaxation function adopted for the analysis showed to be very well adjusted to the experimental results. The determined characteristics of elasticity and damping can be directly used in the analysis of dynamics and the design of face seals.

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