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STUFFING BOX ANALISYS BASED ON SYSTEM DYNAMICS APPROACH

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ABSTRACT

The stuffing box seals are widely used in industry despite to their main drawbacks like their high power loses due to the friction between teh shaft and the gasket and the increase of the leakage during the functioning, due to a decrease of the tightening force. In order to minimize these ones, an optimized over-tightening time schedule must be used. The paper present a new approach of the stuffing box seals problem, treated as dynamic systems, allowing to model and simulate their functioning. By this way, the optimal over-tightening time may be established, allowing to obtain the best performances of the seal.

Keywords: stuffing box seal, system dynamics, modeling, optimization

1. INTRODUCTION

The stuffing box seal principle is to obtain a radial sealing force (between the gasket and shaft) by applying an axial force on the lid (Fig. 1a).

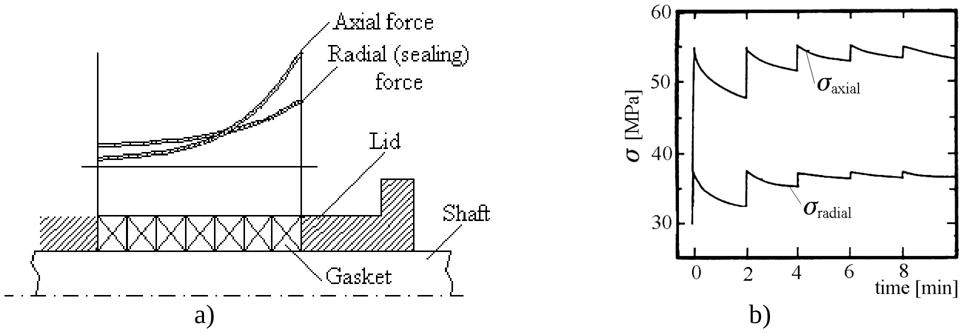


Fig. 1. The stuffing box seal
a) the gasket stresses distribution; b) the gasket stresses evolution in time

As the effect of the friction forces generated between the gasket and the shaft, and between the gasket and the case, respectively, the distribution of the radial stress is non-linear along the shaft [1], following the equation 1:

$$p_R = p_A e^{-\frac{(\mu_1+\mu_2)kL}{S}} \tag{1}$$

where: p_R - the radial pressure, p_A - the axial pressure, $\mu_{1,2}$ - the friction coefficients gasket-shaft, gasket-case, respectively, k - a transformation coefficient, L - the gasket length, S - the gasket thickness.

The main drawback of the stuffing box seals is that, in order to be efficient, there must be a perfect balance between the friction force and the sealing force, this way a minimum power loses and leakage rate can be obtained.

The gaskets used in the stuffing box seals are made of braided polymeric fibers. Due to the micro-structure of these materials (chains of long molecules) and the specific design (long fibers braided in square or round section) they have a visco-elastic behavior. The bulk modulus (K) decreases under constant strain, following the equation 2 [2]:

$$K_t = K_\infty + K_\tau e^{-\frac{t}{\tau_k}} \tag{2}$$

where: K_t - the bulk modulus value at time t, K_∞ - the stabilized value of bulk modulus, K_τ - the bulk modulus decrease rate, τ_k - the relaxation time; t - the time.

As result, during the functioning of the seal, the radial pressure between the gasket and the shaft decreases, leading to a possible leakage. The solution is to increase the axial pressure by over-tightening the lid, according to the relaxation time, specific to the gasket material, but maintaining the friction force at as low values as possible (Fig. 1b).

Taking into account the above, the maintenance of the stuffing box seals is an optimization problem in order to find the right values for the axial tightening force applied to the seal's gasket and for the corresponding time intervals. This may be accomplished either by experimental methods or by computer aided modeling and simulation methods.

2. GASKET MODELING

2.1. Experimental methods

The gasket behavior modeling [3] assumes several measurements to be done, on specialized designed test rigs, using the tested materials, in several functioning conditions with different values for the axial stress, the friction coefficients and the sealed pressure. The obtained values allow to draw some graphs (Fig. 2) and to build numerical models, with constants depending on the particular testing conditions (equation 3). As results, the evolution of radial stresses in the gasket is predicted, allowing the estimation of the optimal axial stress and the over-tightening time. Based on this, the seal's maintenance schedule can be drawn.

$$p_A = Z_{ps}\left(1 - e^{C_L}\right)p_S \tag{3}$$

where:

p_A - the optimal axial pressure,

p_S - the sealed pressure,

Z_{ps}, C_L - experimentally established coefficients.

The main drawback of these methods is that the results' precision is directly influenced by the fidelity that the test rig reproduces the real seal. Thus, good results imply expensive devices or cheap device imply poor results. These methods are efficient just for a single seal type, working in specified environmental conditions.

2.2. Computer aided methods

These methods are generally based on building numerical models starting with the gasket's material properties and specific loading conditions. In [4] the stress distribution along the gasket follows the equation 4:

$$\sigma_Z = \sigma_L e^{\frac{-4(\mu_1 k_1 d + \mu_2 k_2 D) z}{D^2 - d^2}} \tag{4}$$

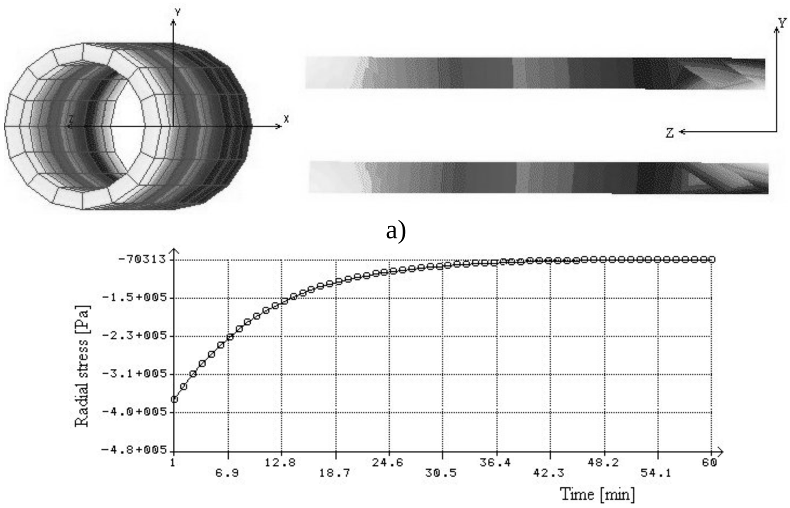
where: σ_Z, σ_L - axial and radial stress in gasket, respectively, $\mu_{1,2}$ - the friction coefficients gasket-shaft, gasket-case, respectively, $k_{1,2}$ - the transformation coefficients gasket-shaft, gasket-case, D, d, z - the shaft diameter, the case diameter and the gasket length, respectively.

Due to the very large areas of the factors influencing the seal's gasket, some simplifying hypotheses must be done, equation 4 becoming:

$$\sigma_Z = \sigma_L e^{-2\mu k \frac{z}{S}} \tag{5}$$

where: σ_Z - the radial stress in gasket; σ_L - the axial stress; μ - the friction coefficient; k - a transformation coefficient; z - the gasket length; S - the gasket thickness, this is the main factor that affects the results precision.

In order to obtain good results as many influences must be taken into account. Using a finite element analysis based method [5], the obtained results can be more extensive: the stress and deformation distributions in the gasket, the evolution graphs for different values of the influencing parameters etc. (Fig. 3).



a)

b)

Fig. 3. Finite element model of a stuffing box gasket
a) the stress distribution; b) the stress evolution in time

The main drawback of these methods is that some specific functioning conditions and influences are difficult to be translated in the numerical equation in order to be included into the model. Also, the modeling and simulation software is usually expensive and the user must have some special skills and training.

3. DYNAMIC SYSTEMS THEORY

The dynamic systems theory states that any entity made of different parts, which maintain its existence through the parts interaction and have some new properties as compared to the components, can be considered as a dynamic system. The only limit is the complexity level at which the observer is willing to stop. As characteristics of a dynamic system, one may praised [6]:

- the system consisting of individual elements;
- among the component elements of the system there are interrelations;
- there is a clear boundary that makes the separation of the system from the surrounding environment;
- the systems have a dynamic behavior, their states changing over in time;
- the systems' elements might be considered as sub-systems or a system might be made of a single element of a larger system.

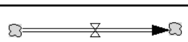
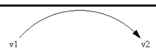
The System Dynamics methodology [7] is used to understand the system changing in time through equations of finite differences or of differential equations. Once the representation of the real system is modeled, one may study the dynamic of the all available states of the system. One of the greatest facility offered by this method is that the feedback connections can be easily modeled and simulated (Fig. 4).

Fig. 4. The feed-back connection

The modeling and the behavior simulation of the dynamic systems is possible with the help of a special kind of computer software. The main advantage of these ones is that the model may be built in a visual way, both the parts and the links between them. The result is a stock-and-flow diagram representing the model of the real system and allowing to run the simulation on, with the time as the main parameter. One of these softwares is Vensim, free for academic use. Vensim uses few variables, as presented in Table 1 [8].

Using the above presented tools, a dynamic model for the stuffing box seals can be built.

Table 2. Vensim modeling variables

Variable type	Signification
Level	Variables that can modify their content during the simulation
Auxiliary	Variables that remain constants during the simulation
	Variables that connect level variables with data flows
⧖ Rate	Variables that control data flows
	System boundaries
	Regular connectors

4. THE STUFFING BOX SEAL AS A DYNAMIC SYSTEM

From the above described point of view, the stuffing box seal can be considered as a dynamic system. The functioning of the seal is conditioned by the interactions among the components and the whole system has a new property (the sealing capacity), different from those of the each part seperately taken.

Taking into account the main factors influencing the stuffing box seal as a dynamic system, a model can be drawn using Vensim software. In table 2 there are presented the elements used for the stuffing box model building.

The radial pressure in thegasket is treated as a level variable in the model, filled by the axial stress and discharged by the relaxation. Other elements from table 2 are modeled as auxiliary variables, having constant values during the simulation, but being modifiable in an optimization stage.

The main connections within the model are made through the equations involving all the parameters: for the axial-radial stress and the bulk modulus, equations 1 and 2 are used.

Table 2. Stuffing box model components

Component	Signification
K0	Initial bulk modulus value
K1	Stabilized bulk modulus value
Bulk modulus relaxation	The rate of bulk modulus relaxation
Relaxation time	Bulk modulus relaxation time
Sealed pressure	Sealed environment pressure
Transformation coefficient	Axial / radial stress ratio
Sliding speed	Linear sliding speed gasket-shaft
Shaft friction force	Friction shaft-gasket
Case friction force	Friction case-gasket
Friction coefficients	Shaft-gasket and case gasket
Roughness	Shaft and case roughness
Gasket geometry	Length / thickness ratio
Axial pressure	Pressure applied to the lid
Radial pressure	Resulting pressure on the shaft
Relaxation	Gasket stress relaxation ratio

The friction force modeling takes into account that in the stuffing box seal there is a static friction between the case and the gasket and the dynamic friction between the shaft and the gasket. Experimental studies [9] show that the evolution of these forces is affected by some parameters like the surfaces' roughness and the sliding speed. Following this, the friction forces' equations are:

$$\begin{gathered} F_{GS} = \sigma_Z \mu_{GS} + C_1 R_S - C_2 S_s \\ F_{CG} = \sigma_Z \mu_{GC} + C_1 R_C \end{gathered} \tag{6}$$

where: F_{GS}, F_{CS} - the friction forces between the gasket-the shaft and the gasket-the case, respectively, μ_{GS}, μ_{CS} - the friction coefficients between the gasket and the shaft and the gasket and the case, respectively; R_S, R_C - the roughness of the shaft and the case, respectively, S_S - the sliding speed between the shaft and the gasket; C_1, C_2 - experimentally established constants.

The other links among the model components are built following the next considerations:

- the bulk modulus relaxation is influenced by the bulk modulus values, the bulk modulus relaxation time and the simulation running time;
- the axial pressure is influenced by the sealed pressure, the bulk modulus relaxation, the shaft friction force and the case friction force;
- the shaft friction force is influenced by the shaft-gasket friction coefficient, the shaft roughness, the radial pressure and the shaft-gasket sliding speed;
- the case friction force is influenced by the case-gasket friction coefficient, the radial pressure and the case roughness;
- the relaxation is influenced by the bulk modulus relaxation, the axial pressure and radial pressure;
- the radial pressure is influenced by the axial pressure, the relaxation, the gasket length/thickness ratio, the transformation coefficient and the shaft and the case friction coefficients.

The obtained cause's tree on the radial pressure and the final model is presented in Fig. 5.

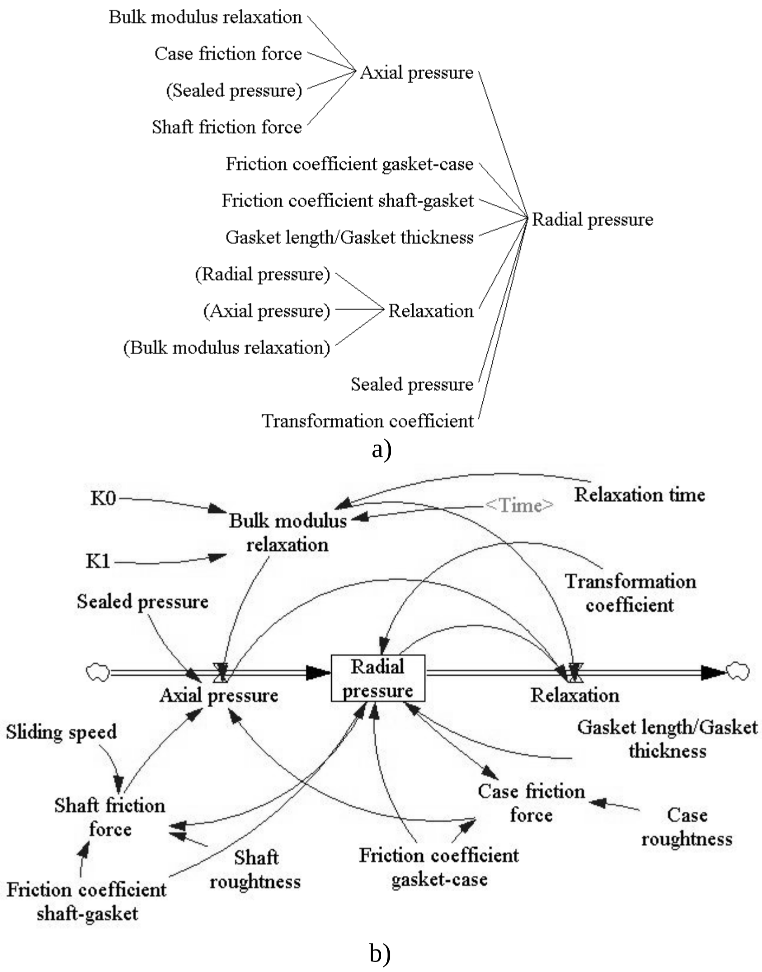
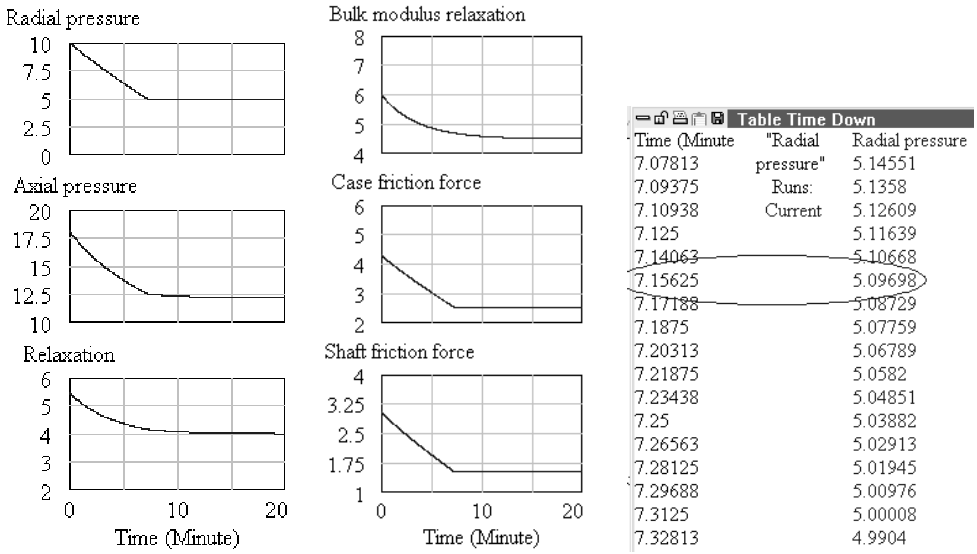


Fig. 5. Modeling stuffing box in Vensim
a) the cause's tree; b) the model

Running the model for a time interval of 20 minutes with a time-step 0.0156 minutes, the evolution of the axial stress, the radial stress, the friction forces and the bulk modulus are obtained (fig. 6).



Time (Minute		Radial pressure
7.07813	"Radial pressure"	5.14551
7.09375	Runs:	5.1358
7.10938	Current	5.12609
7.125		5.11639
7.14063		5.10668
7.15625		5.09698
7.17188		5.08729
7.1875		5.07759
7.20313		5.06789
7.21875		5.0582
7.23438		5.04851
7.25		5.03882
7.26563		5.02913
7.28125		5.01945
7.29688		5.00976
7.3125		5.00008
7.32813		4.9904

a) b) c)

Fig. 6. The modeling results of the stuffing box in Vensim
a) the pressures evolution; b) the additional variables evolution; c) the numerical values

The obtained graphs allow to determine the over-tightening time. This operation should occur somewhere before the moment 7.15625, where the radial pressure value becomes equal to the sealed pressure value (5MPa in the presented example, Fig. 6c).

The model also offers the possibility of optimizing the radial pressure and the over-tightening time values by changing the involved constants (Fig. 7). The cursors attached to each auxiliary variable allow on-the-fly modifications, thus, a certain combination of influencing factors can be established in order to obtain the optimal functioning performances for the stuffing box seal.

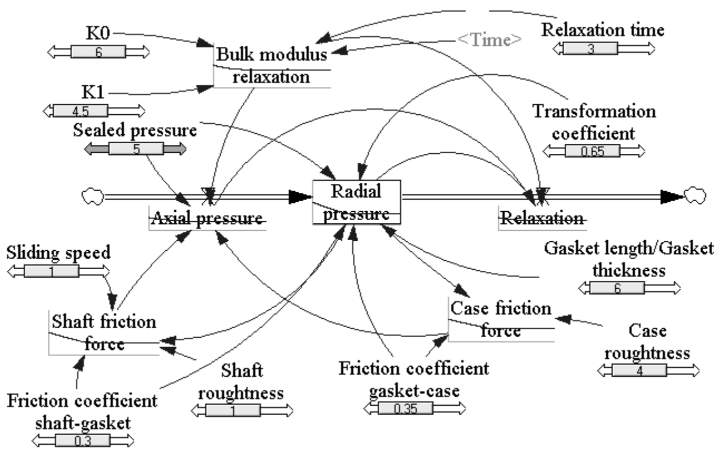


Fig. 7. The optimization with on-the-fly variation of the constants

5. CONCLUSION

The paper presents a new approach for the stuffing box seals study and their optimization. The system dynamics based methodology allows to build a model valid for a large domain of the stuffing box seals, which can provide, by simulation, the values for the most important parameters: the over-tightening time and the axial pressure.

The presented method avoids the necessity of sophisticated test rigs, in order to study the stuffing box seals behavior.

The Vensim software is free for academic use (or much less expensive than a finite element analysis software for non-academic use).

The model allows a simulation with changes in the constants values on-the-fly, standing as a useful and precise tool for seals' designers. The main characteristic geometrical and functioning parameters can be modified in order to study different types of stuffing box seals covering a large area of interest.

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