UDC 621

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# A FEM MODEL OF A HYDRAULIC CYLINDER SEALING COMPONENT

*Сучасне дослідження і розробки, які здійснюються на рішеннях щодо запечатування гідравлічних циліндрів, переважно концентруються на усуненні нафтового витоку в оточенні, скороченні тертя і продовженні операційного часу. Папір представляє нелінійний аналіз емісійної МІКРОСКОПІЇ гумового друку використовував в гідравлічних циліндрах. Досягнута інформація такий тиск, контактні тиски змови для різних видів друку, дозволяє передбачати і покращувати оперативні опечатуючі здібності і бути здатним бути також корисним на роботах щодо носіння процесів. Виконувані моделі і досяг результатів, можливо, використовується надалі, більше розвивав аналізи, покриваючі instroke і outstroke piston батога а також різних теплових умов.*

*Современное исследование и разработки, которые осуществляются на решениях относительно запечатывания гидравлических цилиндров, большей частью концентрируются на устранении нефтяной утечки в окружении, сокращении трения и продолжении операционного времени. Бумага представляет нелинейный анализ эмиссионной МИКРОСКОПИИ резиновых печатей использовал в гидравлических цилиндрах. Достигнутая информация такие давления, контактные давления для различных видов печатей, позволяет предсказывать и улучшать оперативные опечатывающие способности и быть способным быть также полезным на работах относительно ношения процессов. Выполняемые модели и достиг результатов, возможно, используется в дальнейшем, больше развивал анализы, покрывающие instroke и outstroke piston плети а также различных тепловых условий.*

*Modern research and development works which are carried out on solutions regarding sealing of the hydraulic cylinders, are mainly focused on elimination of oil leakage into the environment, reduction of friction and extension of an operation time. The paper presents a nonlinear FEM analysis of elastomeric seals used in hydraulic cylinders. Achieved information such stresses, contact pressure plots for various types of seals, allows to predict and improve operational sealing capabilities and can be also useful on works regarding wearing processes. Performed models and achieved results may be used in further, more developed analyses covering instroke and outstroke of piston rod and also different thermal conditions.*

## 1 Introduction

In every manufacturing process, engineers has to answer the fundamental question: Does the product meet the requirements? In a traditional procedure of manufacturing of elastomeric sealing components, the answer was possible after few major phases. The whole procedure consisted of the design phase, cutting a mold, starting sample production, testing and finally deciding of possible range of changes. Every change in shape of the seal required repetition of the procedure. This traditional method was time-consuming and relatively expensive.

Modern simulation tools allow to rearrange the traditional manufacturing process. After the preliminary design is made, the FEA tools can be employed in order to answer the following question: Does the product probably meet the given requirements? If changes are to be made, they are made in the design phase, and what is most important, before cutting the mold, which is very expensive. The next steps, which are the same as in traditional procedure, mostly demonstrate compliance with initial assumptions and requirements [2].

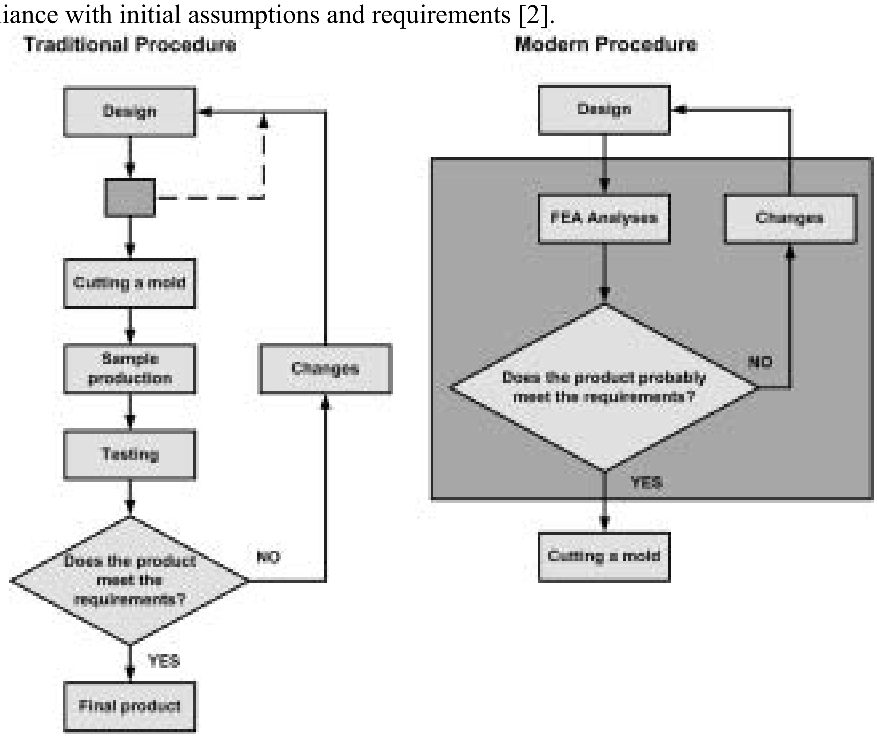


**Fig. 1. Block diagram of traditional and modern manufacturing procedures**

The paper presents a nonlinear FEM analysis of various types of elastomeric sealing rings used in hydraulic cylinders of heavy duty machines.

An analysis of behaviour of hyperelastic rubberlike materials is a complex engineering problem. Occurrence of material nonlinearities, large deformations, friction and possibility of self to self contact require special tools to solve the task.

Increasing computational power of Personal Computers allows to conduct this type of complex simulations in a reasonable time. To conduct FEM analyses shown in this article ANSYS system has been used. This software was chosen due to the large computational capabilities, possibility of inputting data in a batch mode as well as its parametricity (APDL Programming Language).

Five types of sealing rings have been examined. To describe a behaviour of elastomeric material used in following analyses the two parameter Mooney-Rivlin hyperelastic material model has been used.

### 1.1. Hyperelastic Material Model

Hyperelasticity refers to a specific type of materials, that can undergo large elastic strain, without losing initial properties. The constitutive description of hyperelastic materials is based on strain energy density function.

According to [1] and [3]**,** the hyperelastic models are based on the Lagrange description of large deformations. The Green-Lagrange strain tensor **E** is defined as follows:

$$\mathbf{E} = \frac{1}{2}\left(\mathbf{F}^{\mathrm{T}}\mathbf{F} - \mathbf{I}\right) \tag{1}$$

with **F** deformation gradient. A variation of this strain measure is the Right Cauchy-Green stretch tensor **C** given as:

$$\mathbf{C} = \mathbf{F}^{\mathrm{T}}\mathbf{F} \tag{2}$$

The stresses can be calculated from the derivatives of the strain energy density function $W$ to the strains:

$$\mathbf{S} = \frac{\partial W}{\partial \mathbf{E}} = 2\frac{\partial W}{\partial \mathbf{C}} \tag{3}$$

The eigenvalues of **C** (squares of the length ratios in principal directions) are $\lambda_1^2$, $\lambda_2^2$ and $\lambda_3^2$, and exist only if:

$$\det\left(\mathbf{C} - \lambda_{\mathrm{m}}^2\mathbf{I}\right) = 0 \tag{4}$$

Equation (4) can be re-expressed as:

$$\lambda_{\mathrm{m}}^6 - I_1\lambda_{\mathrm{m}}^4 + I_2\lambda_{\mathrm{m}}^2 - I_3 = 0 \tag{5}$$

where $I_1$, $I_2$ and $I_3$ are principal invariants of **C**, defined as:

$$I_1 = \mathrm{tr}(\mathbf{C}) \tag{6}$$

$$I_2 = \frac{1}{2}\left(\mathrm{tr}\left(\mathbf{C}^2\right) - \left(\mathrm{tr}\mathbf{C}\right)^2\right) \tag{7}$$

$$I_3 = \det(\mathbf{C}) \tag{8}$$

Under the assumption that material response is isotropic, it is convenient to express the strain energy density function in terms of strain invariants or principal stretches:

$$W = W\left(I_1, I_2, I_3\right) = W\left(\lambda_1, \lambda_2, \lambda_3\right) \tag{9}$$

The hyperelastic materials are usually considered as purely or nearly incompressible. Thus, the function $W$ is split into a deviatoric part $W_{\mathrm{d}}$ and hydrostatic part $W_{\mathrm{h}}$. The deviatoric part describes a constant volume deformation, the hydrostatic part describes a uniform compression of expansion. To fulfill the separation of the deviatoric and hydrostatic part, a modified set of deformation measures is introduced:

$$J_1 = I_1 I_3^{-\frac{1}{3}} \tag{10}$$

$$J_2 = I_2 I_3^{-\frac{1}{3}} \tag{11}$$

$$J = \sqrt{I_3} \tag{12}$$

or alternatively for the principal stretches:

$$\bar{\lambda}_{\mathrm{m}} = \lambda_{\mathrm{m}} I_3^{-\frac{1}{6}} \tag{13}$$

$$J = \lambda_1\lambda_2\lambda_3 \tag{14}$$

The strain energy density function can be defined as:

$$W = W\left(J_1, J_2, J\right) = W\left(\bar{\lambda}_1, \bar{\lambda}_2, \bar{\lambda}_3, J\right) \tag{15}$$

It is worth noting here, that for purely incompressible materials, the third principal invariant (volume change ratio) $I_3 = 1$ and the new measures do not differ from the originals.

For an incompressible, initially isotropic material, the Rivlin formulation can be used to construct any type of strain energy density function. This formulation can also be used for nearly incompressible materials if the principal invariants $I_1$ and $I_2$ are substituted by the modified invariants $J_1$ and $J_2$. The two parameter Mooney-Rivlin model used in FEM analyses can be derived from Rivlin formulation and it is given as follows:

$$W = c_{10}\left(J_1 - 3\right) + c_{01}(J_2 - 3) + \frac{1}{d}(J - 1)^2 \qquad (16)$$

The initial bulk modulus is:

$$\kappa = \frac{2}{d} \qquad (17)$$

## 2. The Object of Research

Five types of sealing rings used in hydraulic cylinders have been examined. Typical hydraulic cylinder structure with sealing points indicated is shown in Fig. 2. Standard gland is shown in Fig. 3.

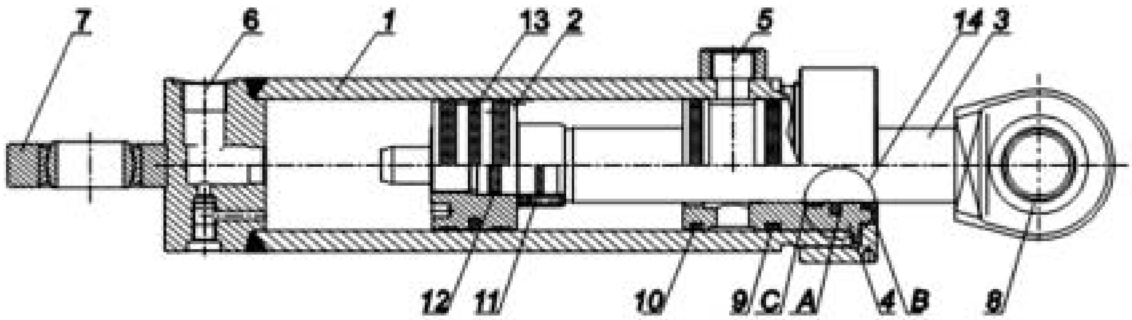


**Fig. 2: Hydraulic cylinder: 1 – Cylinder, 2 – Piston, 3 – Piston rod, 4 – Gland, 5,6 – Channels, 7,8 – Ears, 9,10 – Piston rod gland static seal, 11,12 – Piston static seal, 13 – Piston dynamic seal, 14 – Piston rod dynamic seal, A – Sealing ring, B – Wiper, C – Bearing**

Analysed set of seals consist of an O-Ring, rectangular sealing ring, W10534 and W2563 lip seals, and asymmetrical lip seal with two sealing edges. The general technical data of examined seals are: material – 70A – based on NBR (Acrylonitrile-Butadiene Rubber), nominal hardness 70 IRHD, operating temperature: -30 °C to +100 °C, maximum sealed pressure 16 MPa, maximum velocity of piston rod 0.5 m/s.

**Fig. 3: Gland**

## 3. FEM Analysis of a Cylinder Sealing

The models were created as a batch files for the ANSYS system. An axisymmetric model of a cylinder sealing was used in FEM analysis. The geometry of the piston rod, seal and housing was parametrized, so that to be easily modified or used in an optimization process.

The mesh of the seal was created using PLANE182 (2-D 4-node structural solid quadrilateral) element type with activated mixed u-p formulation option. Contact pairs consist of CONTA171 and TARGE169 elements with both initial geometrical penetration and offset included. Each iteration of contact analysis is based on current mean stress of underlying elements. Isotropic friction model was also applied to contact elements, with the coefficient of friction of 0.2. To avoid problems with solution convergence and to obtain accurate results, the mesh was refined in critical areas. A fine mesh can be seen near to the the initial contact and closure area, on the example of W2563 type lip seal, shown in Fig. 4.

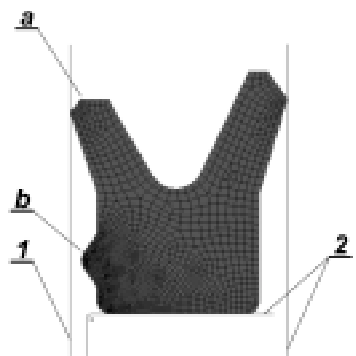


**Fig. 4: Mesh applied on seal model, 1 – Piston rod, 2 – Housing, a, b – sealing edges**

Geometry of housing was simplified and in general consist of three non deformable rigid walls.

The initial interference fit of seal was performed by applying a radial displacement to the piston rod and housing walls. Due to the large deformation for both the interference fit and loading process, the total displacement and total pressure were applied in series of load steps. Direct application of displacement or pressure, may lead to convergence problems and solution instability. The result of nonlinear static analysis (Von Mises stress distribution) of the asymmetrical lip seal with two sealing edges under pressure of 4 MPa is shown in Fig. 5.

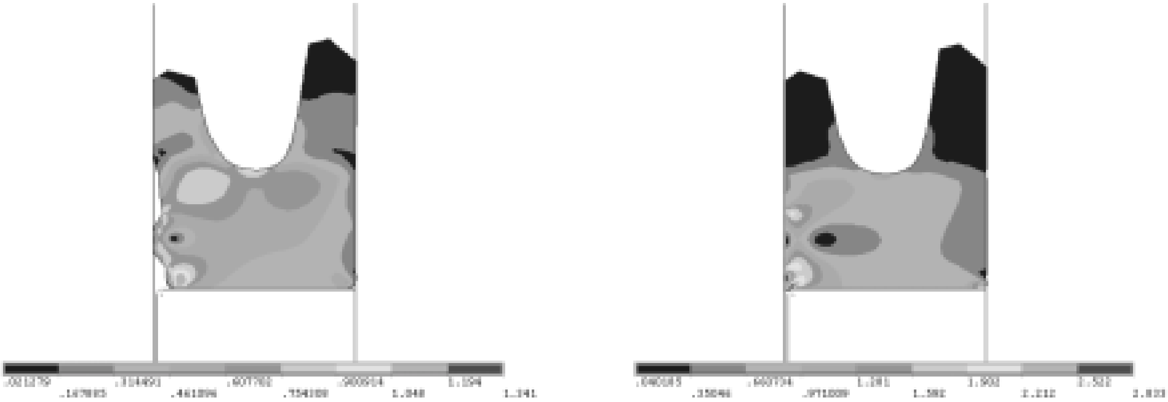

**Fig. 5: Von Mises stress distribution for the asymmetrical lip seal under pressure of 4 MPa (20 % and 100 % simulation time respectively)**

Contact pressure distribution for this case is shown in Fig. 6.

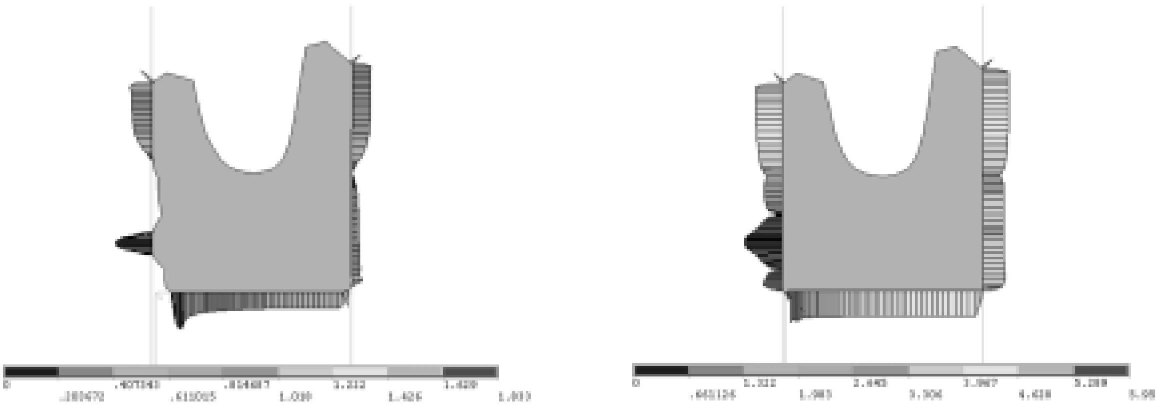

**Fig. 6: Contact pressure distribution for the asymmetrical lip seal under pressure of 4 MPa (20 % and 100 % simulation time respectively)**

An analysis of the sealing under applied pressure shows the deformation processes that can have influence seal wearing. Large deformation and extensive extrusion of seal material into closure can lead to damage in this area. The process of extrusion of the seal material depending on closure size is shown on the example of W2563 lip seal. The result of analysis under pressure of 10 MPa for the closure size of 0.1 mm, is shown in Fig. 7.

Von Mises stress distribution over W2563 seal for closure size of 0.2 mm and sealed pressure of 10 MPa is shown in Fig. 8.

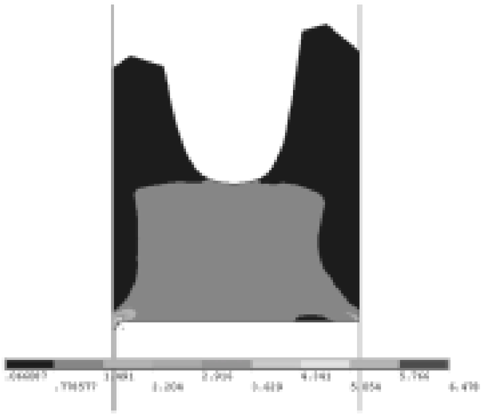

**Fig.7: Von Mises stress distribution for the W2563 lip seal under pressure of 10 MPa (closure 0.1 mm)**

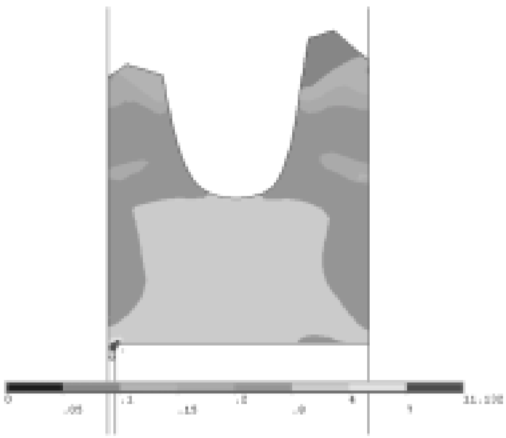

**Fig. 8: Von Mises stress distribution for the W2563 lip seal under pressure of 10 MPa (closure 0.2 mm)**

Due to higher then average contact pressure, also intensified abrasive wear occurs near the closure area. Depending on working conditions, material properties, and groove geometry, the abrasive wear and cutting of outer layer may appear with various intensity. Seals made of less harder material are less endangered for abrasive wear but more for cutting by groove edge [6].

## 4. Conclusion

The paper presents a nonlinear FEM analysis of various solutions of elastomeric seals used in hydraulic cylinders of heavy duty machines. To conduct FEM analyses ANSYS system has been used.

Achieved information such stresses, contact pressure plots for various types of seals allows to predict and improve operational sealing capabilities and can be also useful on works regarding wearing processes. The geometry of the FEM model was parametrized, so that to be easily modified or used in an optimization process.

Performed models and achieved results may be used in further, more developed analyses covering instroke and outstroke of piston rod and also different thermal conditions.

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