Numerical structural analysis of interference seal subjected to hydrostatic pressure

Gabriell Luis Andrusyszyn da Silva[1], Lucas Lincoln Fonseca Soares[1], Roberto Guilherme Lopes[1], Juan Carlos Romero Albino[1], Jhonderson Oliveira Brazil[1], Frederico Garcia de Oliveira[1]
[1] *SENAI CIMATEC, Industrial Product Development, Salvador, Bahia, Brazil*

Abstract: This study presents a detailed finite element analysis (FEA) of an interference-fit lid-type sealing system subjected to high hydrostatic pressure, with a focus on assessing potential leakage risks due to relative displacements. The primary objective was to evaluate whether the applied pressure induces a gap between the lid and the hole, compromising sealing integrity. A simplified yet representative numerical model was developed, incorporating symmetry, interference-fit conditions (penetration depth equivalent to the interference), a friction coefficient (μ = 0.15), and a hydrostatic pressure load of 30 MPa. The analysis employed typical aluminum material properties and accounted for large displacement effects using Ansys® Mechanical. Results demonstrated that the interference fit maintains the lid within the elastic deformation regime, with peak stresses (28 MPa) remaining below the material's yield strength. However, post-pressure application, the hole expanded (+0.0059 mm) while the lid compressed (−0.031 mm), resulting in a relative displacement of 0.037 mm. This gap, though small, could permit fluid leakage depending on viscosity and operational conditions. The findings emphasize that mechanical interference alone is insufficient to guarantee sealing performance under high pressures; instead, coupled material behavior must be considered to prevent failure. The numerical approach enables early-stage design optimization and failure prediction, offering valuable insights for pressurized systems in critical industries such as oil & gas, automotive, and aerospace engineering. Future research directions include material performance comparisons (e.g., composites, high-strength alloys) and experimental validation via CFD simulations or physical testing to quantify leakage rates under real-world conditions.
Keywords: Interference seal; Numerical analysis; Finite elements; Hydrostatic pressure.

1.Introduction

Seals play a fundamental role in various engineering sectors. They are essential components in numerous engineering systems, ensuring the leak-tightness of hydraulic and pneumatic systems by preventing pressurized fluid leakage [1]. In industrial applications, seal failures are among the leading causes of operational costs, compromising safety, energy efficiency, and environmental integrity.

Seals can be implemented in various ways using gaskets, seals, O-rings, or even lids, depending on the application and operational conditions. Gaskets, often made of flexible or metallic materials, are widely used for static sealing in flanges and connections, ensuring leak-tightness through proper compression between flat surfaces. O-rings are circular elastomeric seals that function through elastic deformation, creating an effective barrier against leakage in hydraulic and pneumatic systems [2]. Their popularity stems from ease of manufacturing, low cost, and excellent performance under various pressure and temperature conditions. Additionally, sealing lids can be used in applications where mechanical interference fits are feasible. In these cases, the lid is installed in a hole with an interference fit, promoting sufficient compression and contact to prevent fluid passage. This sealing type is common in components requiring periodic disassembly, such as pump covers, valves, and pressurized vessels. The effectiveness of interference-fit sealing depends on the lid material, dimensional tolerances, and applied hydrostatic pressure - factors that can be evaluated through structural numerical analyses.

Effective sealing occurs when the contact deformation exceeds the fluid pressure [3]. Material selection is crucial for ensuring seal effectiveness, particularly under extreme operating conditions such as high pressures, elevated temperatures, or repetitive loading cycles. Elastomeric materials, widely used in seals due to their deformation and recovery capabilities, require hyperelastic constitutive models to accurately describe their nonlinear behavior under compression and cyclic loading [4]. These models are rigorously calibrated through experimental tests, including uniaxial tension, compression, planar strain, and biaxial tests, which determine the constitutive parameters essential for realistic material performance simulations.

In this context, numerical analysis becomes an indispensable tool for evaluating and predicting seal performance. Computational simulations enable investigation of material and component behavior under varying pressure, temperature, and load conditions, reducing reliance on costly and time-consuming experimental testing. This approach allows early identification of potential failures, seal design optimization, and operational performance prediction, contributing to more reliable and efficient solutions.

Numerous studies in literature employ numerical analyses to predict different seal behaviors. In Zhang et al. [5], finite element analysis was combined with experimental testing to investigate contact pressure distribution in composite sealing rings used in hydraulic supports. The study focused on mechanical interaction between ring materials and adjacent surfaces, emphasizing geometry and material property effects on sealing effectiveness.

Wang et al. [6] conducted a detailed investigation of sealing characteristics in rings used in hydropneumatic springs. The study involved numerical simulations using the finite element method (FEM), experimentally validated using a 2D axisymmetric model in ABAQUS software. The model incorporated the hyperelastic behavior of NBR (nitrile rubber), enabling precise analysis of contact pressure distribution under different compression levels and cyclic loads.

Zhang et al. [7] analyzed the performance of Y-ring rubber seals in hydraulic systems, also using the finite element method. The simulation considered stresses, strains, and contact pressure between the ring and sealing surfaces under different operational conditions. The model adopted hyperelastic properties to evaluate the seal's response to load and pressure variations, providing relevant insights for material selection and geometric optimization.

This work presents a structural finite element analysis of an interference-fit sealing lid subjected to hydrostatic pressure. The analysis aimed to verify whether relative displacement between the lid and hole could create sufficient clearance to enable fluid leakage.

2. Methodology

In numerical analysis, the first step was to verify the possibility of simplifying the geometric model. For this purpose, some details of the lid were removed, keeping only the essential parts and their dimensions. Additionally, symmetry conditions were considered to reduce computational costs. To simulate the effects of interference fitting, the geometric model includes penetration equal to the interference value.
Friction between the thread faces and the aluminum hole was considered, with μ = 0.15 adopted. The interference value adopted in the symmetric model was equal to 0.025 mm. The simulation was executed in two stages: the first being the resolution of the interference and the second the application of 30 MPa hydrostatic pressure to all parts of the model, that is, the lid and the aluminum hole structure (except on the symmetry faces, Figure 1).
Regarding the adopted materials, Table 1 presents the values of the properties necessary for the simulation, all taken from the Ansys® Workbench 2025R1 software library.
The finite element model was generated with hexahedral volumes, resulting in a mesh with 373,612 nodes and 85,844 elements. Due to the high applied pressure, it was considered necessary to include large displacement effects. With the complete model defined, the simulation was executed in Ansys® Mechanical as a static analysis, and from the results it was possible to analyze the displacement field to understand whether clearance occurred between the lid and the hole.

3. Results and Discussion

The presented results consist essentially of the von Mises stress field and displacement field. Figure 2 shows the stress field in the lid, corresponding to the final stage of interference resolution and hydrostatic pressure application. With a yield strength equal to 28 MPa, it is observed that the interference was sufficient to maintain the lid material in the elastic regime (maximum of 21.092 MPa), which is the desirable behavior in an interference fit. The stress tended to increase closer to the outer part of the seal. Note that after pressure application, the stresses decreased significantly.
Figure 3 presents the radial displacement field relative to the hole and lid threads at the final stage of hydrostatic pressure application. The maximum displacement in the hole region was approximately +0.00593 mm (expansion), at the point where the thread with highest stresses is located. For the lid, the maximum displacement was constant at -0.03105 mm (compression). Consequently, there was relative displacement between the parts, generating a clearance of approximately 0.03698 mm.

4. Final considerations

Through the results of this work, it was verified that even though the interference maintained the material in the elastic regime, the applied pressure was sufficient to counteract the thread displacement caused by the interference. Due to the material properties and operating conditions, a clearance formed between the hole and the lid, which could potentially allow fluid passage depending on its viscosity.

As a continuation of this work, we propose analyzing results for different lid materials, as well as verifying whether fluid passage would actually occur with a defined viscosity - either through experimental means or numerically via CFD.

References

[1] Sukumar T, Bapu BR, Prasad BD. Determination of sealing pressure in hyperelastic O-ring with different hardness using numerical method. Journal of Elastomers & Plastics. 2018;51(7-8):684-697. doi:10.1177/0095244318817889

[2] Robert Flitney, "Seals and Sealing Handbook 6th edition," Butterworth-Heinemann, (2014). doi.org/10.1016/C2012-0-03302-9

[3] Song W, Cui W. Finite element analysis of large-sized O-rings used in deep-ocean pressure chambers. *Advances in Mechanical Engineering*. 2021;13(8). doi:10.1177/16878140211040672

[4] Jing S, Mu A, Zhou Y, Xie L. Finite-element analysis and structure optimization of X-O composite seal of cone bit. Advances in Mechanical Engineering. 2014;12(5). doi:10.1177/1687814020918686

[5] Zhang X, Wang G, Xia P, Li H-P, He M. Finite element analysis and experimental study on contact pressure of hydraulic support bud-shaped composite sealing ring. Advances in Mechanical Engineering. trat2016;8(10). doi:10.1177/1687814016674846

[6] Wang, S.; Liu, P.; Li, D.; Dong, Z.; Li, G. Simulation and Experimental Study on Sealing Characteristics of Hydro-Pneumatic Spring GS Seal Rings. Appl. Sci. 2023, 13, 11703. https://doi.org/10.3390/app132111703

[7] ZHANG, X.; LI, J.; WANG, Y. Finite Element Analysis and Simulation of the Sealing Performance of Y-Ring Rubber Seal. *Advanced Materials Research*, v. 444-445, p. 1379–1384, 2012. DOI: 10.4028/www.scientific.net/AMM.444-445.1379.

Figure 1. Model representation: in finite elements made in Ansys® Mechanical, geometric interference, boundary condition and loading.

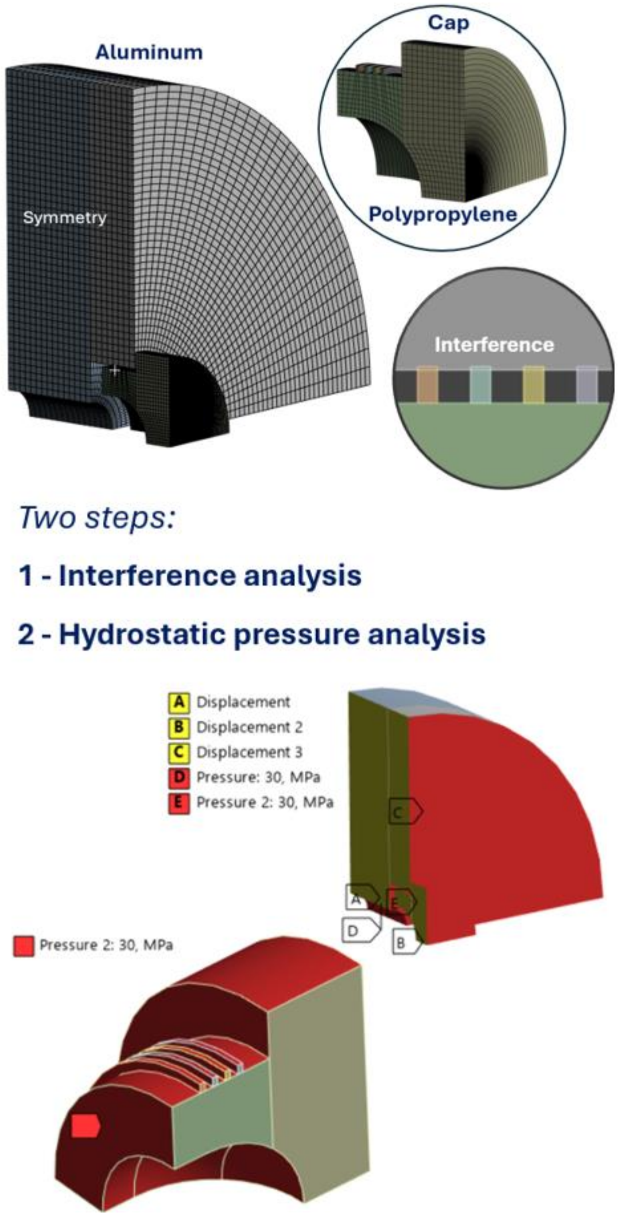
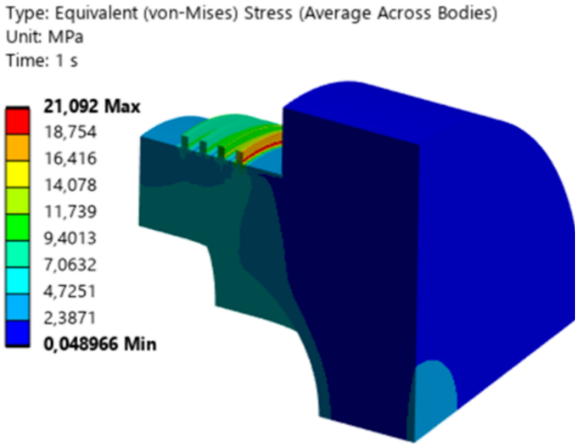
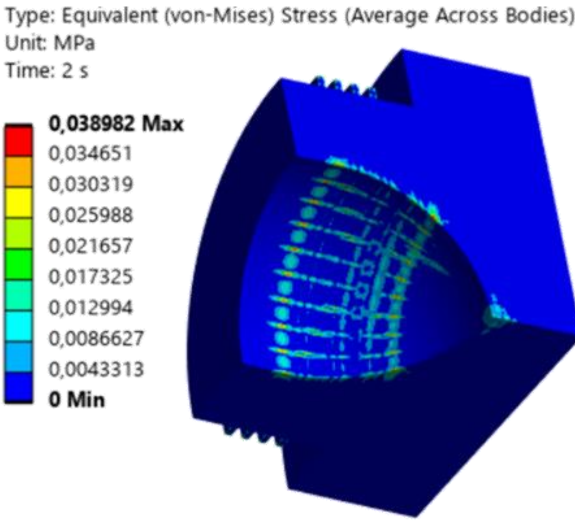


Figure 2. Von-Mises stress field on the lid for interference analysis (a) and hydrostatic pressure (b).

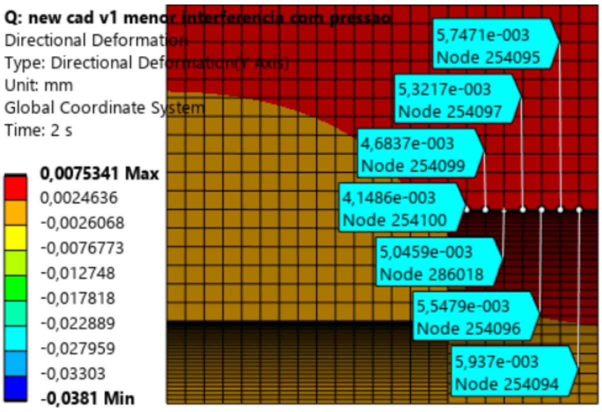


(a)

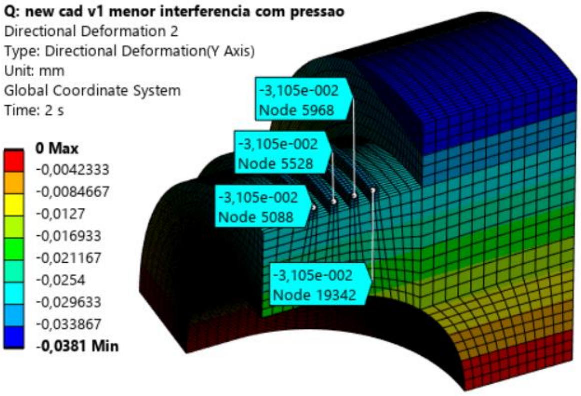


(b)

Figure 3. Radial displacement field in the aluminum hole (a) and in the polymeric cap (b).



(a)



(b)

Table 1. Properties of the materials used.

	Young's modulus (GPa)	Poisson	Density (kg/m³)
Polypropylene	1,6	0,42	870
Aluminum	71,0	0,33	2770