Radial Lip Seal Simulation Using ANSYS Non-Standard Procedures

Zhichao Wang - Sr. Lead Engineer, Applied Mechanics Dept.

Don Draper – Manager, Applied Mechanics Dept.

Tom Hodapp – Sr. Engineering Specialist, AC Engineering

Emerson Climate Technology

Abstract

Elastomer and PTFE lip seals are widely used in industries such as engines and other mechanical devices. The amplitude and distribution of seal contact pressure are major factors affecting seal performance and wear. Contact surface profile changes continuously due to material worn off. Worn off material has to be removed from FE models continuously to obtain a realistic solution and uncover the mechanism of seal wear. Non standard ANSYS rezoning procedure and APDL macros have been developed to investigate PTFE lip seal wear and improve product reliability in this paper.

Introduction

Various elastomer and PTFE material are used in the manufacture of radial lip seals particularly, PTFE, due to its low friction coefficients, greater temperature range, and chemical resistance properties. Lip seals are widely used in aircraft, automobile, and compressor industry. A variety of lip seal configurations are available in the market. Two lip seals are shown in Figure 1; (a) is spring energized, generally made using elastomer and (b) is pressure loaded, PTFE lip seal.

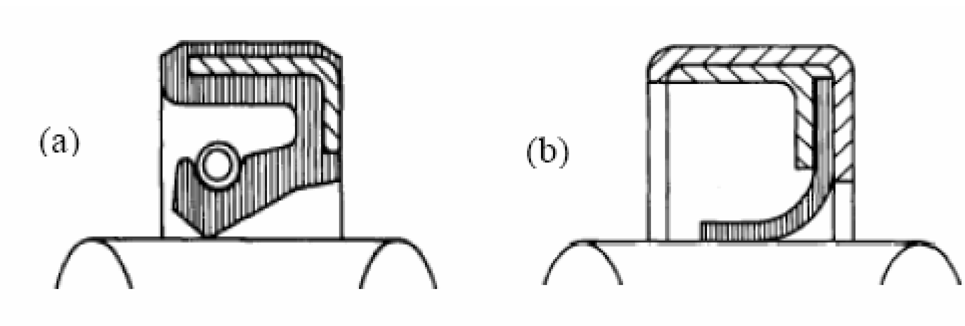

Figure 1. Lip Seals

Important considerations in lip seal design are: wear resistance, temperature range, service life and cost. Wear of lip seal materials is a major concern in seal design. As well as directly affecting seal component life, wear and associated loss of seal performance may lead to accelerated bearing, shaft, and product failure. Many factors affect seal wear and performance such as contact pressure, sliding velocity, temperature, surface finish, and lubrication. The contact pressure is critical in seal design, performance, and failure analysis. It is hard to measure the contact pressure distribution of an actual lip seal. This is due to the smallness of contact band and the complexity in both the material properties and the environment. FEA is a powerful tool to evaluate seal stress, strain, and contact pressure distribution. It is still a challenging subject to accurately compute seal contact pressure and deformation due to the complexity of seal material behavior. Emersion Climate Technologies has been using ANSYS to assist compressor seal design and quality improvement successfully in recent years.

The amplitude and distribution of contact pressure of seals is strongly dependent on the contact area of the interface. The contact area changes continuously due to material worn off. The contact area and seal deformation can be dramatically different without considering the reduction in thickness of the seal due to

wear. The worn off material has to be removed continuously from cycle to cycle to simulate seal wear and improve design.

The PTFE material is strongly non linear in loading, unloading and reloading. It is temperature dependent, time dependent, and pressure sensitive. Hence, the stress strain history of the seal has to be preserved during solution steps due to its geometric and material nonlinearities. This can be done through ANSYS non standard application. Both ANSYS single and multi frame restart procedures will keep the history. But the multi-frame will use the geometry of the first substep. The geometry stored in rdb file cannot be modified by users. The single frame-restart use geometry stored in db file. Db file can be modified between solutions. Thus single frame restart procedure can be used to preserve the solution history and remove the worn off material using modified geometry from step to step. The PTFE material samples were tested at three temperatures, three strain rates for both tension and compression. Perzyna's viscoplastic constitutive models were used. The method and procedures of seal contact pressure evaluation and wear simulation are discussed below.

Material Models

Under the hypothesis that the elastic, plastic, and viscous strain can be separated, the total strain of a material may be expressed as Equation 1. Most polymers such as PTFE material is temperatures dependent, time dependent and pressure sensitive (different in compression and tension) as shown in Figure 2. Multilinear Von Mises constitutive model combined with Perzyna's rate dependent viscoplastic model are used in this study. The elastoplastic model is used to represent the Elastoplastic behavior. And Perzyna's viscoplastic constitutive model was used to cover the effect of strain rate on material properties, Equation (2).

$$\underset{\sim}{\varepsilon} = \underset{\sim}{\varepsilon}^{e} + \underset{\sim}{\varepsilon}^{p} + \underset{\sim}{\varepsilon}^{v} \quad (1)$$

Where $\underset{\sim}{\varepsilon}^{e}$, $\underset{\sim}{\varepsilon}^{p}$, $\underset{\sim}{\varepsilon}^{v}$ are elastic, plastic, and viscoplastic strain tensors, respectively.

Material Test and Elastoplastic Stress Strain Curves

Three PTFE materials have been tested at three temperatures and three strain rates for both compression and tension. Figure 2 showed the 15% glass PTFE tensile and compressive stress and strain curves. Temperature dependent and rate dependent behavior of PTFE were considered in this simulation. The pressure sensitive, non-linear unloading and reloading behavior were not included because these features are not available and a user program is needed (This work is in progress but not completed).

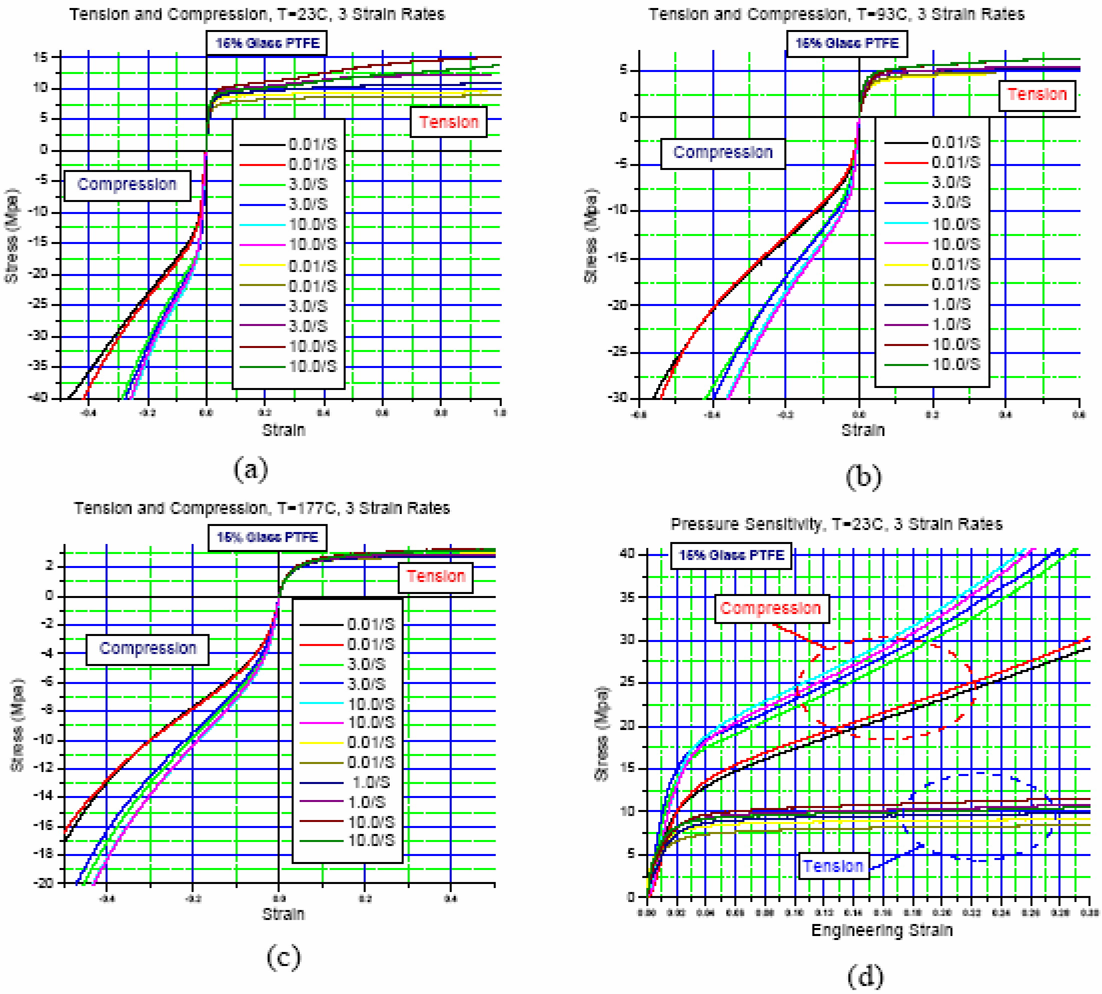

Figure 2. 15% Glass PTFE Stress Strain Curves

Viscoplastic Model and Parameters

ANSYS has two categories of material models for solid materials that are time dependent. The creep models that can combine with most of elastic and plastic material models to simulate material long term time dependent behavior such as creep or stress relaxation or both. Rate dependent models such as Peirce, Perzyna's and Anand models are used to characterize the influence of strain or loading speed on material's time dependent behavior. In this simulation the influence of temperature and strain rate on the seal behavior is considered. Perzyna's viscoplastic constitutive model, Equation (2), is used to consider the influence of strain rate on material's properties.

$$\sigma^e = \left(1 + \left(\frac{\dot{\varepsilon}^v(T)}{\gamma(T)}\right)^{m(T)}\right)\sigma_0(T, \dot{\varepsilon}) \qquad (2)$$

Where σ^e, $\dot{\varepsilon}^v$ are equivalent stress and viscoplastic strain rate. T is temperature. γ and m are material parameters that can be evaluated through curve fitting as shown in Figure 3 and Table 1.

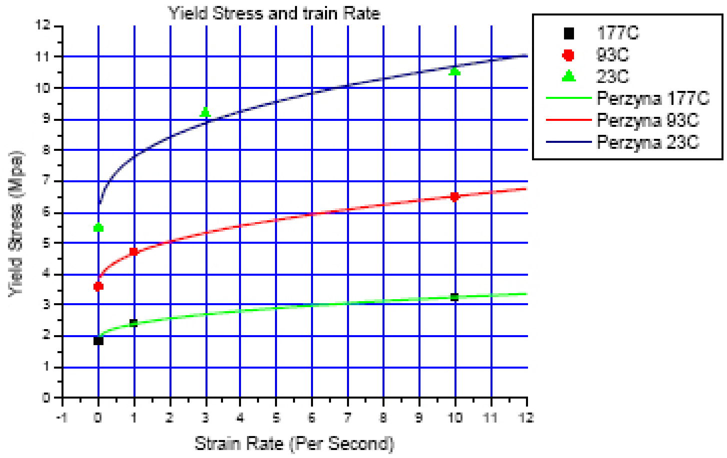

Figure 3. Yield Stress Vs. Strain Rate

Table 1. Parameters of Perzyna's Model

Temperature	m	γ	σ_y
23C	0.42	20.0	1.86
93C	0.44	16.6	3.62
177C	0.36	11.6	5.5

Seal Contact Pressures at Different Temperatures

Figure 4 shows the PTFE lip seal geometry used in this paper. The seal works in a large range of temperature and fluid pressure. The seal may lose contact to the shaft due to plastic deformation and wear. A garter spring is used to create a small radial force to prevent the seal from losing contact before the running pressure is build up. A longer flexible leg is required for the seal to follow the shaft during running. The garter spring force is not needed once the working pressure is developed. Thus the garter spring needs to be designed to provide enough radial force to close the seal gap and as soft as possible to reduce wear.

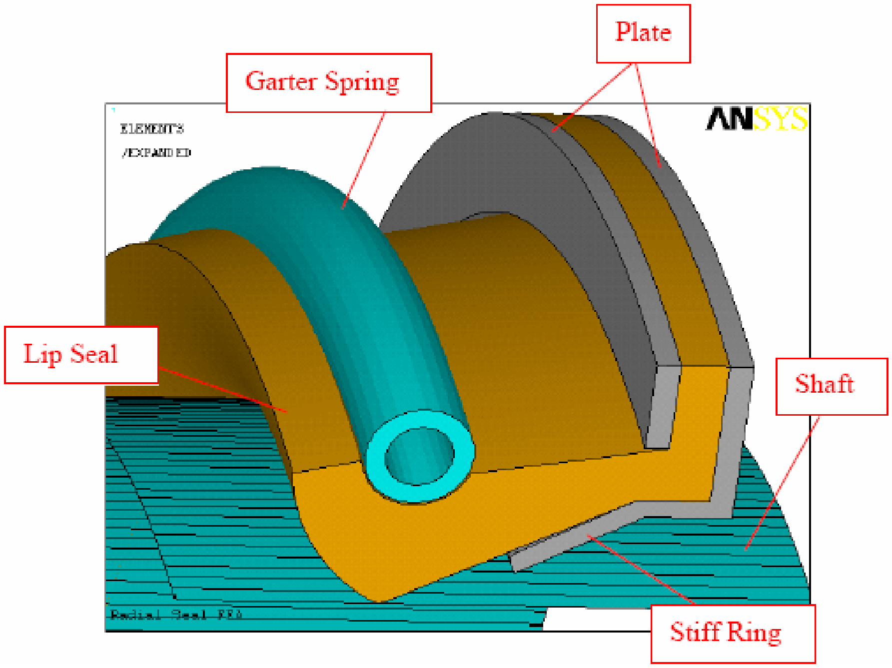

Figure 4. Lip Seal Geometry

Calibration of Spring Tension Force

2-D axisymmetric model was used in this simulation, as shown in Figure 4. The garter spring was included in the model and simulated using 2-D axisymmetric elements. Figure 5 showed the loads and boundary conditions. Multilinear elastic material model is used to simulate the garter spring force deflection behavior as shown in Figure 6. The calibrated material parameters are given in Table 2. The dependence of material properties of the spring on temperature was ignored compared with that of the PTFE seal material.

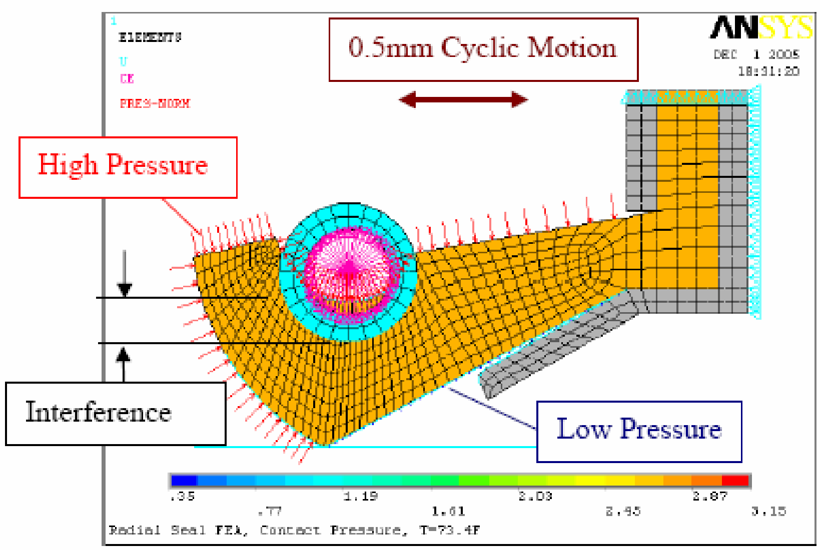

Figure 5. Load and Boundary Condition

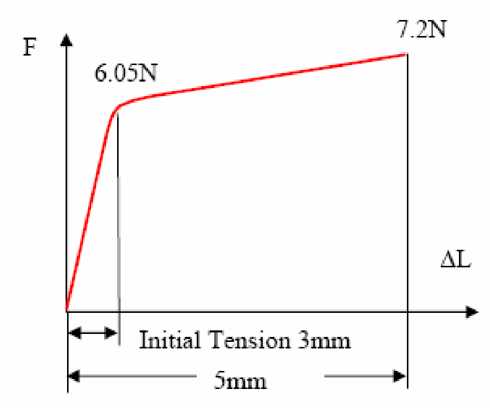

Figure 6. Tension Deflection Curve of the Garter Spring

Table 2. Garter Spring Parameter

	Stress
0.0172	2.4853
0.4172	11.831

Computation of Contact Pressures at Different Temperatures

Using the material models discussed above, the initial contact pressures at three different temperatures were calculated and plotted as shown in Figure 7. Figure 8 showed the dependence of the contact pressure on the temperature. Constant fluid pressures were applied on the two sides of the seal for the purpose to see the dependence of seal contact pressure and distribution on the temperature. In reality, the fluid pressure changes with the temperature.

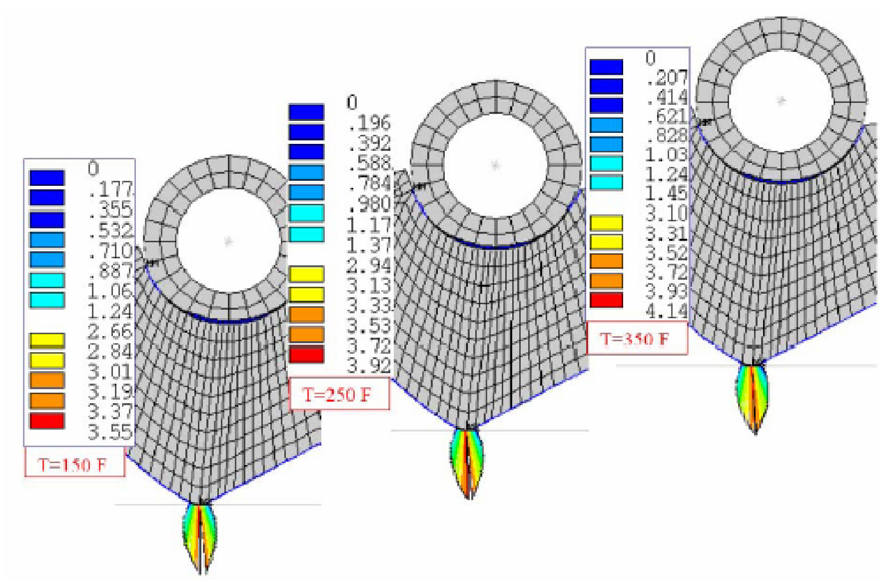

Figure 7. Seal Contact Pressure and Distribution at Different Temperatures

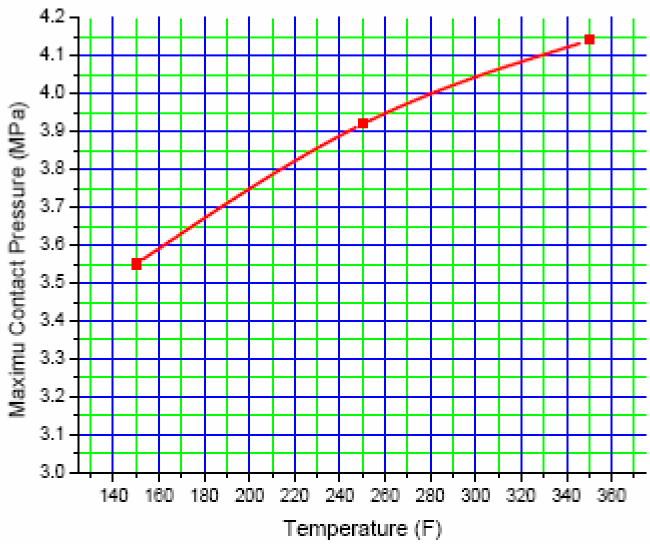

Figure 8. Dependence of Seal Contact Pressure on Temperature

Methods of Lip Seal Wear Simulation

Element death and birth

ANSYS element death and birth technique can be used to remove material from the model between solution steps. The advantage using element death and birth technique is that deactivating elements is a standard ANSYS feature and this technique is well developed. The disadvantage is that the material to be removed has to be meshed before the solution is obtained. We know that the profile of contact and the contact pressure change continuously. The material worn off is directly depending on the contact pressure. Thus where and how much the material will be removed are unknown in advance. In addition, contact pressure is very sensitive to the geometry of the contact profile. The material can not be removed continuously as a smooth function of contact pressure due to the limitation of size and location of elements to be deactivated. It is also hard to create multi-layers of contact elements and achieve convergence due to large distortion of deactivated elements.

Rezoning (Moving nodes and restart)

Material wear rate is generally depending on the contact pressure, sliding velocity and surface condition. For a given surface condition, the rate of material wear is proportional to the PV value (The product of pressure and velocity). This requires that the material removed has to be a function of the contact pressure. In other words, the contact zone has to be remeshed (rezoning) as a function of the PV value. And the stress strain history has to be reserved for the remaining zone. Thus an ANSYS non standard rezoning procedure and macro programs were developed through ANSYS single frame restart features as discussed above. Restart will preserve the solution history required for nonlinear problems. Moving nodes using solutions of previous load step and saving the modified geometry into db file from step to step can be used to remove the material. Then the mesh of the zone to be remeshed can be modified continuously as a function of the contact pressure and sliding velocity.

FEA Procedures (Flow Chart)

Function of Material Worn Off

Material wear rate varies depending on material, contact pressure, surface roughness, temperature, and sliding velocity. Wear test needs to be done to obtain material wear rate for specific application. Wear rate for most elastomer and PTFE may be available from seal manufactures. Seal material wear test is usually conducted on a fairly simple apparatus such as the pin on disk [1, 3], ring on block [4], Pin on plate [5], and Ball on disc [6]. The rate of material worn off can then be expressed as,

$$Dt = f(p, v, T, \xi) \qquad (3)$$

Where Dt is the loss of thickness due to wear, p, v and T are contact pressure, sliding velocity and temperature. ξ represents the surface condition. This function can be evaluated based on material test results. For steady state wear, a linear function may be used. $Dt = a*P_{cont,}$ is used in this paper.

Computation Procedures

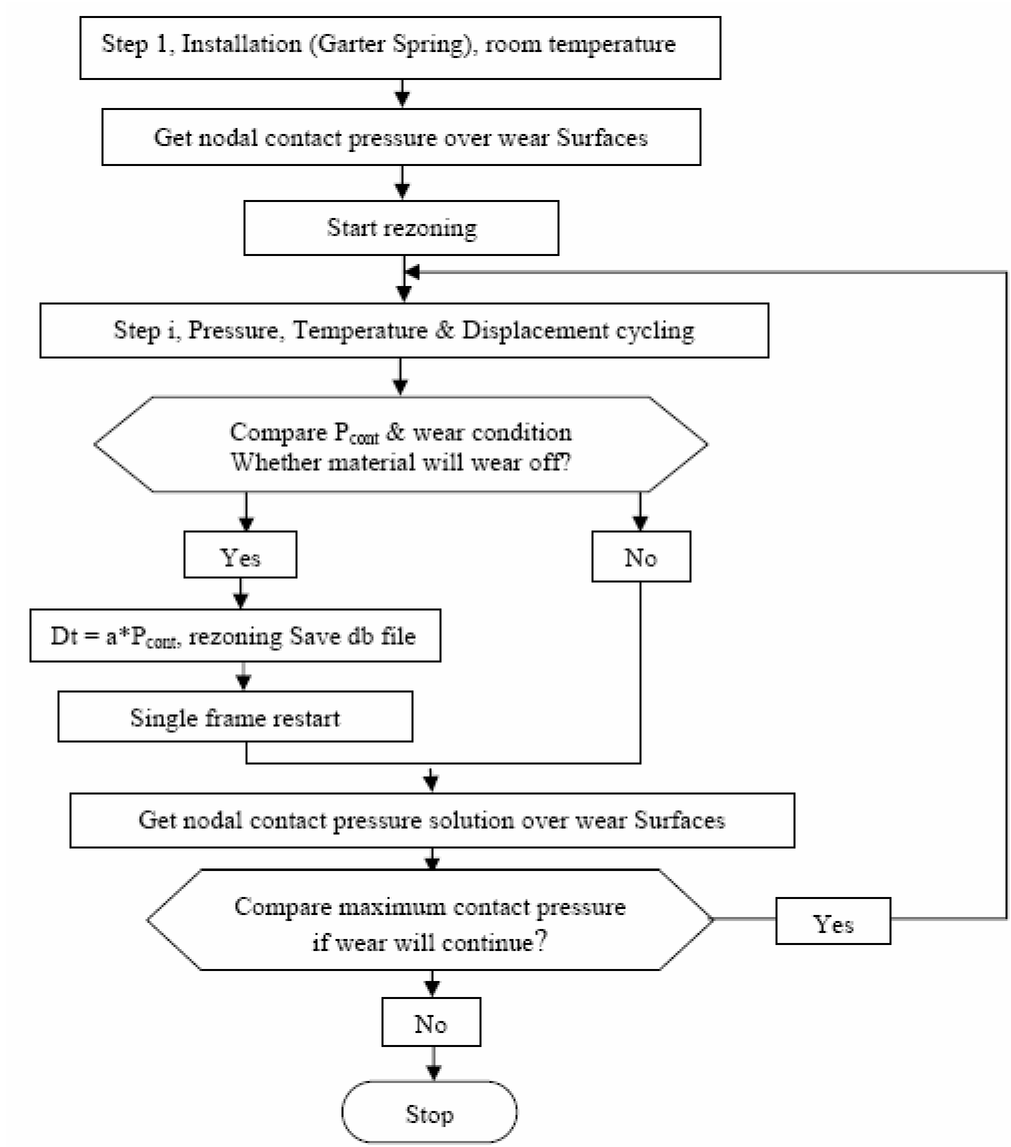

Figure 9. Computing Flow Chart

Results and Wear Progress

FE Model, Load & BC

Figure 10 illustrated loading profiles of pressure differential, temperature cycles, and axial displacement under running condition of the seal. Material temperature dependent behavior and strain rate effect were considered in this simulation.

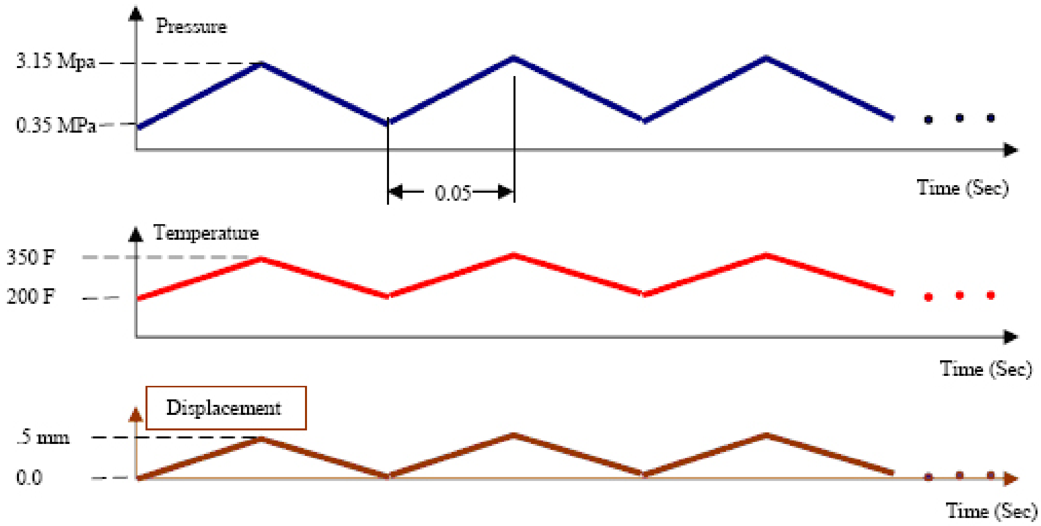

Figure 10. Loading Profile

Contact Pressure Variation due to Wear

Rezoning procedure as shown in Figure 9 and APDL macros were developed in the simulation of radial seal wear. Results are given below. Figure 11 showed the process of material removed from cycle to cycle as a smooth function of the contact pressure. Figure 12 showed the evolution of contact pressure with the progress of material worn off or the number of cycles. This reveals that both the distribution and the amplitude of the contact pressure of the seal change continuously due to the loss of material. This behavior cannot be achieved without removing the worn off material from the model.

Seal Geometry with Worn off Material Removed

Figure 13 compared the seal geometry at the end of the first load cycle with that at the end of the 100th load cycle. The amount of reduction in thickness is about 0.45 mm. An accelerated wear rate can be used for the purpose to evaluate wear, leakage, and improvement of the seal design. The actual wear rate is required to determine whether the lip seal will wear. Results showed that this ANSYS non-standard procedure is a powerful tool for seal wear simulation.

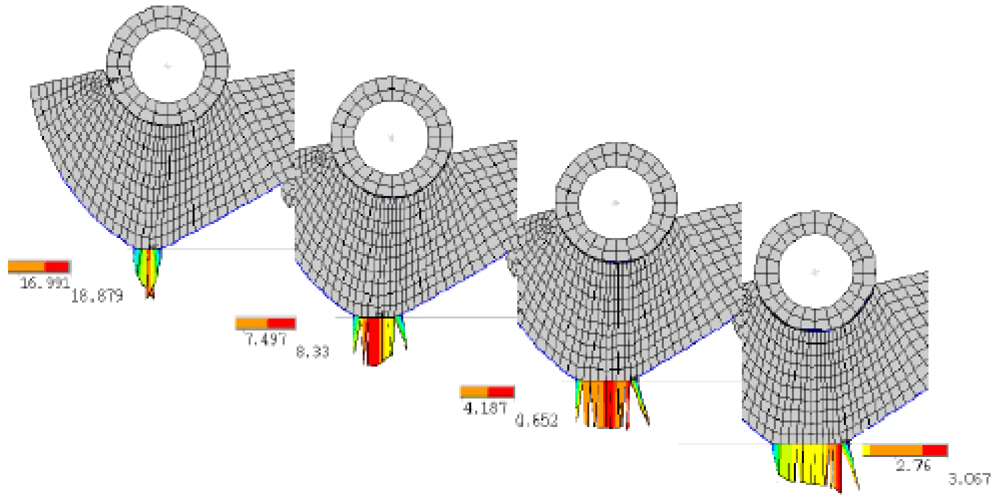

Figure 11. Evolution of Seal Contact Pressure and Seal Wear

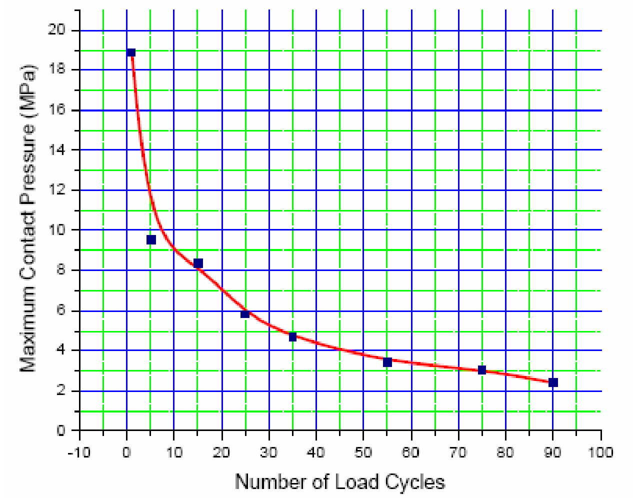

Figure 12. Variation of Seal Contact Pressure with the Number of Cycles

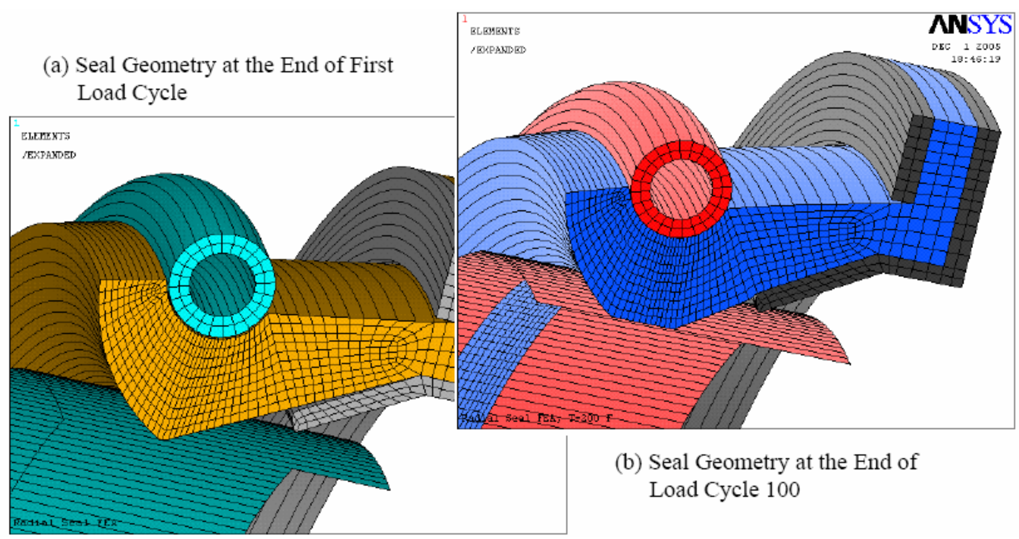

Figure 13. Comparison of Seal Geometry due to Wear

Conclusion

Garter spring parameters were obtained. Garter spring was included in the FE model. PTFE Material was tested. Perzyna's constitutive model was used and material parameters were evaluated.

ANSYS APDL macros and nonstandard rezoning procedures were developed for the computation of PTFE lip seal contact pressure with and without wear. FEA results showed that this ANSYS nonstandard rezoning procedure can be a powerful tool in seal design, failure analysis, and the improvement of seal reliability.

Two methods can be used in the simulation of lip seal severe wear, the element death and birth technique and rezoning. Rezoning technique will provide a smooth removal of the worn off material as a function of contact pressure and sliding velocity. Thus a realistic simulation can be achieved compared with the element death and birth technique. PTFE lip seal wear was simulated successfully.

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