# Numerical Study of Friction Behavior In Pneumatic Seal Cylinder

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**Abstract.** This study presented the development of numerical model to investigate the behavior of the friction force between piston seal and cylinder bore. Two-dimensional finite element model with constant velocity input was built. Numerical simulation showed the same trend as the experimental results from literature, with different of less than 5%. This comparison indicated that numerical model can be used for further simulation. At the end of the study, the friction force behavior for different stroke lengths were shown.

**Keywords:** *finite element analysis, pneumatic seal, friction force, stroke length*

## 1 Introduction

Pneumatic cylinder is a device that can produce force in reciprocating linear motion with low cost, simple construction, and easy maintenance, which are the most wanted properties in industrial automation. However, there are several factors that can reduce the performance of pneumatic cylinder, one of which is seal malfunction.

Seal malfunction is mostly caused by the friction between piston seal and cylinder bore. The friction behavior of elastomer seal of pneumatic piston with different velocity and air pressure was observed experimentally by Raparelli, et al [1]. This study showed that the friction force has linear relationship with respect to piston velocity and air pressure. Friction force itself is directly related to the friction coefficient and normal force, while normal force is linearly proportional to the contact pressure between seal and cylinder bore. Experimental study of contact pressure between piston seal and cylinder bore have been investigated under dry and lubricated condition by Belforte, et al [2]. The results showed that lubricated condition did not give much effect to the contact pressure. Another experimental study of the friction seal pneumatic in different conditions

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were carried out by Azzi, et al [3]. This study analyzed the behavior of friction in many conditions, one of them is the behavior of friction force when velocity of the piston is constant during outstroke and instroke movement.

Mikó [4], on the other hand, has performed numerical simulation of the frictional contact analysis between piston seal and cylinder bore. Two dimensional elements with hyper elastic material were used in order to generate the friction force. Three friction characteristics were analyzed during simulation: Coulomb, extended Coulomb and the Benson-Hallquist model. The numerical simulation was then validated experimentally. The numerical results showed that the frictional force decreased exponentially with respect to the piston velocity in Benson-Hallquist model at low velocity.

In order to shorten analysis time and save the cost, numerical model of pneumatic cylinder is needed. Simulation for different conditions are necessary, such as the variation of piston diameter and stroke length. This paper aims to develop the numerical model of the friction behavior of pneumatic seal for different stroke length. Two numerical model with different dimensions to analyze the frictional contact was built, which then validated by experimental data from literature.

## 2 Methodology

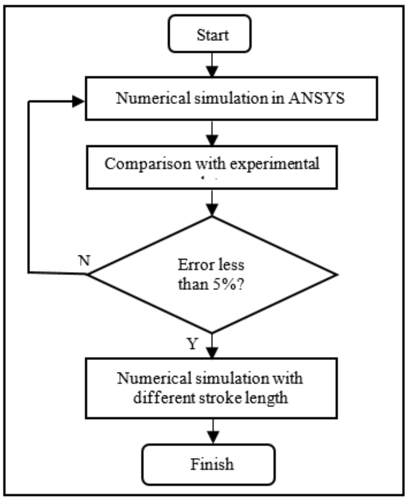


**Figure 1** Research Methodology

This paper deals with the finite element analysis of friction force between piston seal and cylinder bore with different stroke length. Two-dimensional model was developed in ANSYS to shorten the computational time. The results from numerical simulation was then compared to the experimental data which has been conducted by Azzi, et al [3]. The methodology of this research is presented in figure 1 below.

### 2.1 Friction Force

Friction force is a resistive force between two contacting surface which has opposite direction with respect to component's motion. There are several types of friction model, one of them is widely known as coulomb friction. Coulomb friction force for non-moving objects is expressed by the multiplication between its static friction coefficient ($\mu_s$) and normal force ($F_N$) exerted between contact surface as shown in equation 1.

$$F_c = \mu_s F_N \quad (1)$$

If external force exceeds the limit of the static friction, then the object moves, and the friction force is multiplication of its dynamic friction coefficient ($\mu_d$) and normal force ($F_N$) as expressed in equation 2.

$$F_c = \mu_d F_N \quad (2)$$

In the case of pneumatic cylinder, the friction force is resistive force between seal and cylinder bore. Location of pneumatic cylinder main components are shown in figure 2.

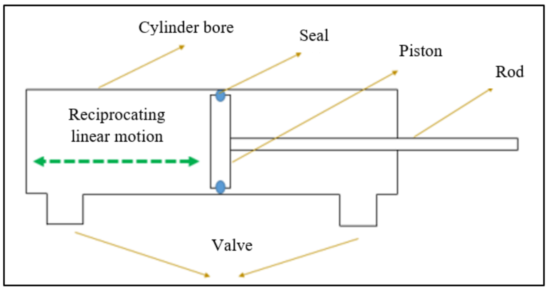


**Figure 2** Main parts of pneumatic cylinder

Reciprocating linear motion of piston starts when air pressure comes inside to the cylinder from the opened valve and push the piston for reciprocating linear motion as shown in figure 3. The input force is multiplication of supplied air pressure and area of piston.

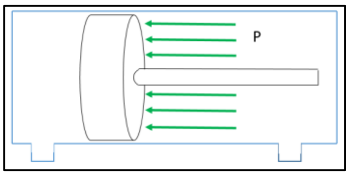


**Figure 3** Input force from air pressure

Friction force is the dissipated force during piston movement. According to newton's law, equation of motion can be written in the following form:

$$\sum F = m.a \tag{3}$$

$$p.A - F_{friction} = m.a$$

$$F_{friction} = p.A - m.a \tag{4}$$

Experimentally, inertia force can be measured by using accelerometer sensor, while friction force is force different between external force from air pressure and measured inertia force, as shown in figure 4.

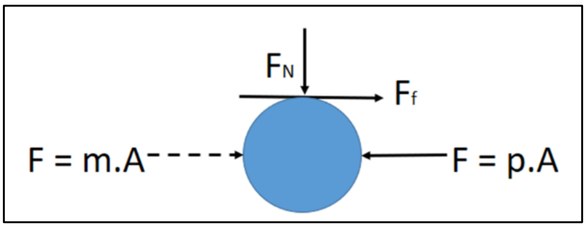


**Figure 4** Free body diagram of seal

## 2.2 Finite Element Analysis

From figure 2, it can be concluded that geometry of piston seal and cylinder bore can be simplified into two-dimensional element model due to friction force location occurred at the contact region between piston seal and cylinder bore. ANSYS requires some data in order to conduct numerical simulation, such as material specification, contact region definition, boundary condition, and load condition. The setup of the current model followed the setup of the experiment which was conducted by Azzi, et al [3].

### 2.2.1 Material Specification and Contact Region

The material of piston and cylinder are aluminum alloy, in which the data have been provided in ANSYS material data, while seal rubber material is defined as Neo Hooken material. Information about material properties were obtained from the numerical simulation that has been performed by Mikó [4]. Piston and seal contact region are defined as bonded contact region because these components are not separable during operation, while the contact region between seal and cylinder bore is defined as frictional contact region. Table 1 presented the material properties and dimensions needed for simulation.

**Table 1** Seal rubber material specification and piston dimension for simulation

| | |
|---|---|
| Density | 1310 kg/m$^3$ |
| Friction coefficient | 0.7 |
| Initial shear module ($G_0$) | 44 MPa |
| Incompressibility parameter ($D_1$) | 6.67 x 10$^{-4}$ MPa$^{-1}$ |
| Cylinder bore diameter | 64 mm |
| Stroke length | 250 mm |

### 2.2.2 Boundary and Load Condition

In pneumatic system, piston moves up and down, while cylinder bore is fixed at its position. In this numerical study, cylinder bore is defined as fixed support, while piston is set up as the load condition with constant velocity 50 mm/s in Y-axis as shown in figure 5.

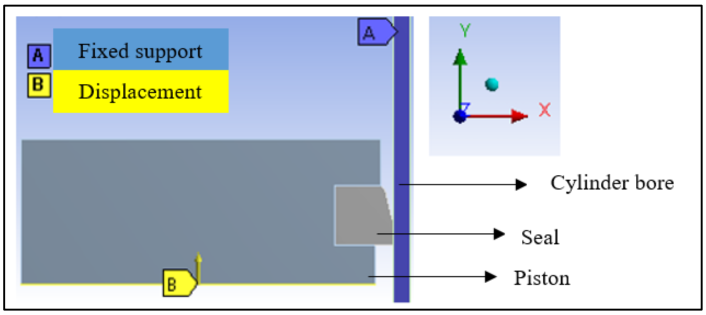


**Figure 5** Two-Dimensional Finite Element Model

In order to simplify the analysis, displacement as the function of time is used instead of velocity function and is defined in 5 steps. First step is displacement along X-axis for 0.67 mm as constant part, and second to fifth step is displacement along Y-axis from 0 mm to 250 mm as function of time with time step of 5 seconds. Displacement along Y-axis for each step represents the reciprocating linear movement from initial position (0 mm) to final position (250 mm) and come back to initial position as one cycle. Load step and reciprocating linear motion are presented in table 2 and figure 6.

**Table 2** Load step

| Step | Time (Second) | Displacement (X-axis) | Displacement (Y-axis) |
|---|---|---|---|
| 1 | 0.02 | 0.67 | 0 |
| 2 | 5 | 0.67 | 250 |
| 3 | 10 | 0.67 | 0 |
| 4 | 15 | 0.67 | 250 |
| 5 | 20 | 0.67 | 0 |

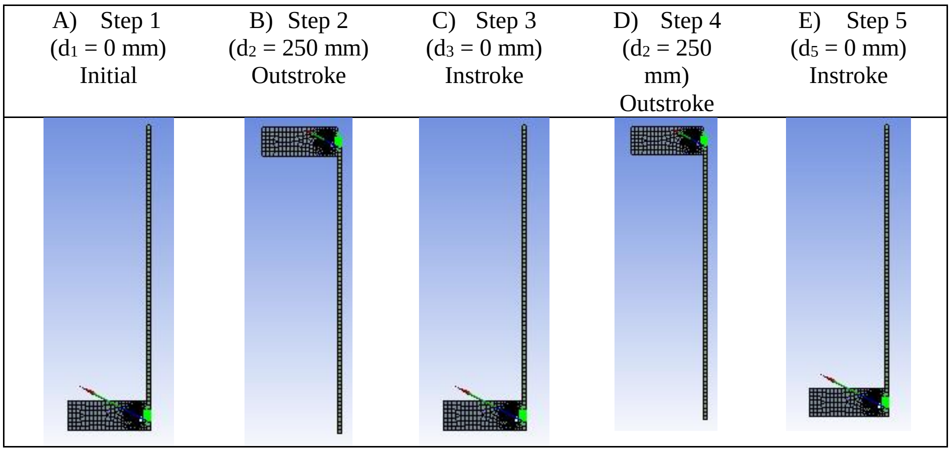


**Figure 6** Reciprocating Linear motion

### 2.2.3 Numerical Friction Force

When piston move up (Outstroke) and move down (Instroke) along Y axis, reaction force is generated at the contact region between seal and cylinder bore. Based on the free body diagram in figure 4, reaction force along X-axis represented normal contact force, while reaction at Y-axis is defined as friction force. Figure 7 showed the reaction force generated at Y-axis. Validation of numerical model will be presented in the next part.

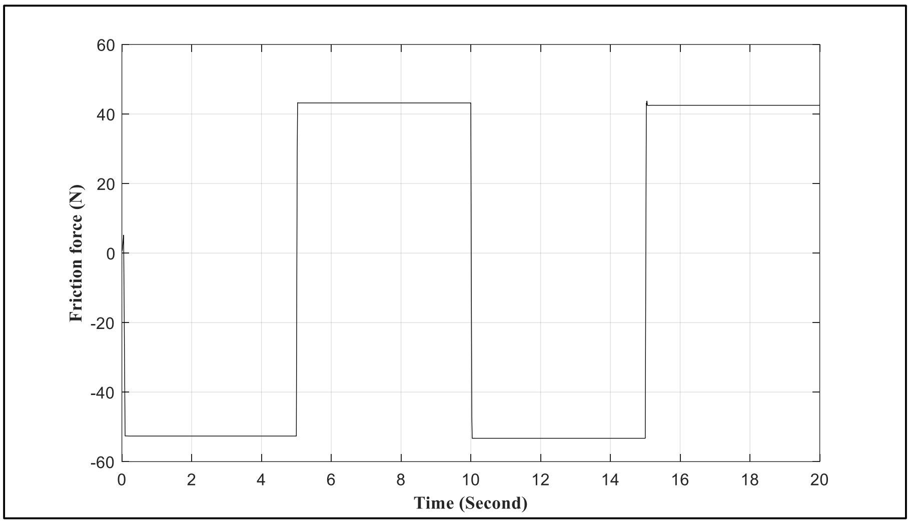


**Figure 7** Numerical friction force

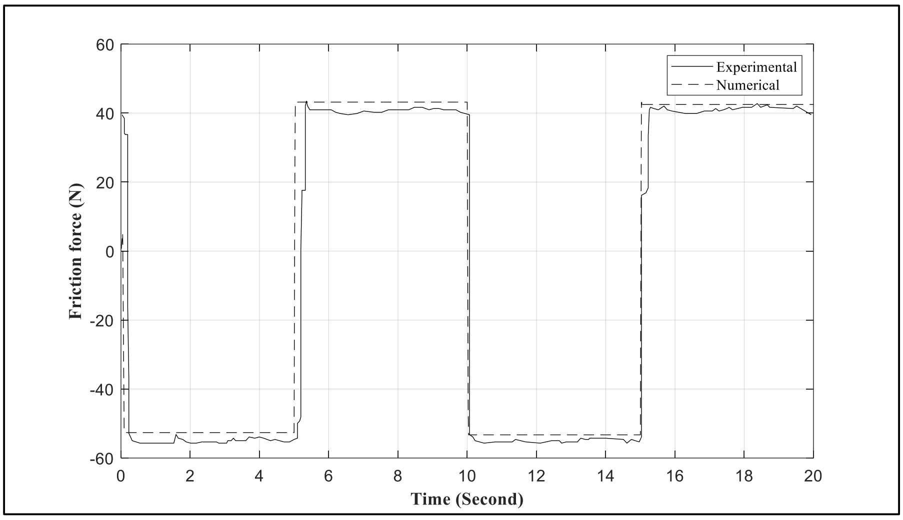


**Figure 8** Comparison between numerical simulation and experimental data from literature [3].

## 3 Results and Discussion

In order to obtain the correct numerical model, results of finite element analysis must be validated either experimentally or analytically. After the numerical model is validated, then further numerical study on the friction behavior due to parameter modification can be performed.

### 3.1 Numerical Model Validation

From figure 5, it can be concluded that the magnitude of friction force is 43 N and -53 N. Negative sign indicates that the direction of reaction force is in opposite direction of Y axis, which means the piston is in moving up along Y axis. This numerical simulation results were compared to experimental data which has been conducted by Azzi, *et al* [3]. Comparison of numerical model and experimental data was presented at figure 8 and table 3.

**Table 3** Friction Force Error for Instroke and Outstroke movement

| Parameter | Maximum Friction Force (N) | | Error (%) |
|---|---|---|---|
| | Experimental Data | Numerical Simulation | |
| Maximum force (Instroke) | 43.5 | 43.7 | 0.6% |
| Minimum Force (Outstroke) | -55.7 | -53.3 | -4.3% |

From the initial results shown in figure 8 above, it can be concluded that numerical simulation shows same trend as experimental data. Table 3 also indicated that the magnitudes of the finite element analysis error are less than 5%, which means the model can be used for further analysis.

### 3.2 Friction Behavior for Different Stroke Length

This study investigated the friction force behavior in different stroke length, with other parameters are kept being constant, such as velocity, friction coefficient, cylinder bore diameter, and the material properties as well. Different stroke length with constant velocity means different time interval and load step, which are presented in table 4. Figure 9 showed the friction behavior with the variation of stroke length.

**Table 4** Different load step for different stroke length

| Stroke Length (mm) | Velocity (mm/s) | Load 1 (Move Up /Instroke) | Load 2 (Move down/ Outstroke) | Load 3 (Move Up /Instroke) | Load 4 (Move down/ Outstroke) |
|---|---|---|---|---|---|
| | | Time (S) | Time (S) | Time (S) | Time (S) |
| 250 | 50 | 5 | 10 | 15 | 20 |
| 450 | 50 | 9 | 18 | 27 | 36 |
| 550 | 50 | 11 | 22 | 33 | 44 |
| 625 | 50 | 12.5 | 25 | 37.5 | 50 |

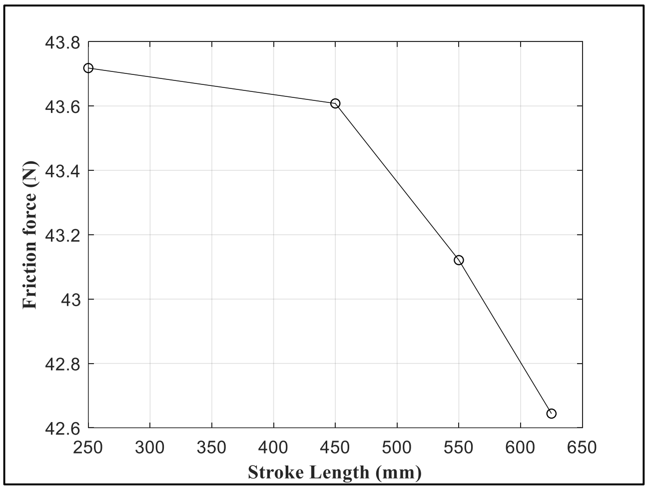


**Figure 9** Friction behavior with different stroke length

It can be concluded that friction force is inversely proportional to the stroke length as shown in figure 9. Longer stroke length generates smaller friction force, and vice versa.

## 4 Conclusion and Future Works

From the numerical results and validation, it can be concluded that two-dimensional finite element analysis can be used to predict the friction behavior of the pneumatic seal cylinder for constant velocity input. Numerical simulation results matched well with the experimental results, with error magnitude of less than 5% for both instroke and outstroke movement. Thus, it gives confidence in applying the current numerical model in the further study on pneumatic cylinder's friction behavior. Prediction on the friction behavior of different stroke length with constant velocity showed that the friction force is inversely proportional to the length of stroke. Longer stroke length generates smaller friction force, and vice versa.

In the near future, further numerical model to get the friction force behavior at different condition will be performed especially for different seal types or different load condition. In order to perform these simulations in the future, sequential methodology which has been developed in this study might be useful.

## 5 Nomenclature

| | | |
|---|---|---|
| $P$ | = | Air pressure supply |
| $A$ | = | Piston area |
| $m$ | = | Moving object mass |
| $a$ | = | Moving object acceleration |
| $f_{friction}$ | = | Friction force |
| $\mu_s$ | = | Static friction coefficient |
| $\mu_d$ | = | Dynamic friction coefficient |

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