



## ESTIMATION OF THE FRICTION PARAMETERS OF LINEAR PNEUMATIC CYLINDERS

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### Keywords

*Pneumatic Cylinder,  
Friction Force,  
Experimental Method.*

### Abstract

Nowadays, pneumatic actuation systems are utilized in many applications due to their outstanding advantages. However, the pneumatics possess nonlinear characteristics that complicate precise motion control. To extend the use of pneumatic actuators to different precise applications their non-linearity should be evaluated and compensated. This is only possible by correctly estimating the non-linear parameters that exist in pneumatic systems. The friction forces in pneumatic cylinders is one of the main nonlinear parameters. These parameters cannot be defined directly or listed precisely for any produced particular cylinder in manufacturer's catalog. They should be estimated accurately by experimental methods. This paper presents a new, simple and cheap experimental method for identification of friction force parameters for standard linear double acting pneumatic cylinders. Two different pneumatic cylinders have been examined with the proposed method and it has been seen that the results sound promising to use in later control applications.

## DOĞRUSAL PNÖMATİK SİLİNDİRLERİN SÜRTÜNME PARAMETRELERİNİN TAHMİNİ

### Anahtar Kelimeler

*Pnömatik Silindir,  
Sürtünme Kuvveti,  
Deneysel Yöntem.*

### Öz

Günümüzde pnömatik aktüatör sistemleri öne çıkan avantajlarından dolayı birçok uygulamada tercih edilmektedirler. Fakat bu sistemler hassas hareket kontrolünü zorlaştıran lineer olmayan karakteristikler barındırırlar. Pnömatik aktüatörlerin kullanımlarını farklı hassas uygulamalara da genişletebilmek için, doğrusal olmayan özelliklerinin belirlenip telafi edilmesi gerekir. Bunun tek yolu pnömatik sistemlerde mevcut olan doğrusal olmayan parametrelerin doğru bir şekilde tahmin edilmesidir. Pnömatik silindirlerdeki sürtünme kuvvetleri esas doğrusal olmayan parametrelerdir. Bu parametreler direkt olarak belirlenemezler ve üretici kataloglarında üretilen herhangi bir belirli silindir için hassas bir şekilde belirtilmezler. Bu parametrelerin deneysel yollarla hassas bir şekilde belirlenmesi gerekmektedir. Bu çalışma, standart, düz çift etkili pnömatik silindirlerin sürtünme kuvveti parametrelerinin saptanması için yeni, basit ve ucuz bir deneysel yöntem sunmaktadır. Önerilen yöntemle iki farklı pnömatik silindir incelenmiş ve sonuçların daha sonraki kontrol uygulamalarında kullanılması umut verici olduğu görülmüştür.

### Alıntı / Cite

Dağdelen, M., Sarıgeçili, M.İ., (2020). Estimation of The Friction Parameters of Linear Pneumatic Cylinders, Journal of Engineering Sciences and Design. 8(2), 397-406.

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### Makale Süreci / Article Process

<b>Başvuru Tarihi / Submission Date</b>	23.05.2019
<b>Revizyon Tarihi / Revision Date</b>	19.12.2019
<b>Kabul Tarihi / Accepted Date</b>	25.04.2020
<b>Yayın Tarihi / Published Date</b>	25.06.2020

## 1. Introduction

Pneumatics are used as actuation systems widely in the applications of industry, medical science and robotic science (Harris et al., 2012; Dağdelen & Sarıgeçili, 2017). The pneumatics find also applications as specific as the

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rotation of a crank shaft in the form of pneumatic muscles as shown in Korucu et al. (2015). The pneumatic actuation systems have outstanding properties such as high power to weight ratio, high compliancy and safety, easy to maintain and fast response to commands (Guenter et al., 2006; Földi et al., 2011; Hejrati & Najafi, 2013). Even though they are preferred widely in many different type of applications, their main drawback is their non-linear behavior due to air compressibility, friction and stick-slip of sealing elements. (Wang et al., 2004; Andrighetto et al., 2006). They are mainly applied as on-off controlled elements with solenoid valves in most of the industrial applications which do not require precision control. However, they need more complex control strategies for precise motion behavior compared to the simple position control. In the complex control algorithms, the main scope is to control both the position and force relationship of pneumatic actuators together. Hence, application of these algorithms are highly dependent on estimation of the friction parameters of pneumatic cylinders. Unfortunately, accurate and precise values of friction parameters for any particular cylinder do not exist (cannot be listed) in catalogs of manufacturers.

A simple expression for pneumatic friction force is generally provided as in the form of Eq.1 in literature (e.g. Andrighetto et al., 2006). However, this expression (Eq.1) is not satisfactory for most of the control applications of pneumatic actuators since viscous friction coefficient,  $B$  is not included in the equation. The expression includes only friction coefficient ( $\mu$ ), working pressure ( $P$ ) and piston effective area ( $A$ ).

$$F_f = \mu * P * A \quad (1)$$

There are many suggestions for friction coefficient values in literature. But, there is no useful information on how to determine this coefficient. Generally, the suggestion of  $\mu$  value ranges between 0.02 and 0.20 as stated in Andrighetto et al. (2006). More detailed friction models should be included in modeling of pneumatic cylinders' applications for better control.

Generally, friction models include basic Coulomb, static, viscous and Stribeck type of friction (Liu et al., 2015; Lafmejani et al., 2016; Saleem et al., 2009). More detailed friction models such as Dahl (Dahl, 1968), Karnopp (Karnopp, 1985), LuGre (de Wit et al., 1995), Elastoplastic (Dupont et al., 2000), Leuven (Swevers et al., 2000), Generalized Maxwell Slip (Al-Bender et al., 2005), and modified LuGre model (Saha et al., 2016) exist in literature for any sliding mechanical system. According to the type of application, one of these friction models is selected and this model is chosen for pneumatic cylinder dynamics (Eq.2).

In literature, the researchers studied different friction models for pneumatic cylinders as well. Belforte and Raparelli (1989) proposed an experimental expression for friction forces in pneumatic cylinders. They tested different types of pneumatic cylinders and provided a general friction force equation. Wang et al. (2004) applied Static-Coulomb friction model and utilized Genetic Algorithms method for parameter estimation. Andrighetto et al. (2006) used Stribeck friction model and proposed an experimental method to define Stribeck friction parameters for different types and sizes of cylinders. Basic Static-Coulomb-Viscous friction model is selected by Saleem et al. (2009). They presented Mixed-Reality Environment method for determination of static, Coulomb and viscous friction parameters in pneumatic cylinders. Chang et al. (2012) studied the friction characteristics of pneumatics cylinders under dry and lubricated conditions. Bo Tran et al. (2013) proposed new modified LuGre friction model for pneumatic cylinders and they developed an experimental method to define the parameters of modified LuGre model for pneumatic cylinders. Richter et al. (2014) also utilized improved LuGre model for special pneumatic cylinders. They aimed to find friction parameters with a software application. Stribeck friction model is also preferred by Kosari & Moosavian (2015) for pneumatic cylinders. They proposed Recursive Least Square algorithm with the aid of experimental setup. Lafmejani et al. (2016) proposed a method to define Coulomb-viscous friction model parameters for pneumatic cylinders.

The methods studied are mostly complex friction models. When complex friction models are used in dynamic modeling of pneumatic cylinders, it gets harder to define the friction parameters. In conclusion, a basic and faster method should be developed for friction identification of standard pneumatic cylinders. Hence, this study aims at utilizing basic Coulomb-viscous friction model for pneumatic cylinders because this friction model can enable good control opportunity for the most of pneumatic control applications (Kosari & Moosavian, 2015). For that reason, an experimental setup is constructed. Pneumatic cylinders' Coulomb friction force ( $F_c$ ) and viscous friction coefficient ( $B$ ) are estimated by evaluating the data from experimental setup. To simplify the equations and parameter evaluation process, the experiments take place on horizontal plane eliminating gravitational effects.

2. Material and Method

2.1. Mathematical Model

The general dynamic model of standard pneumatic cylinders can be given as in Eq.2. In this equation,  $M$  is the total mass that corresponds to the summation of piston-rod mass ( $M_p$ ) (Fig.1) and excessive payload mass ( $M_e$ ) (if exist on the system).  $\ddot{x}$  represents the acceleration of total moving mass  $M$ .  $F_{net}$  is the net output force acting on total mass of  $M$ .  $F_{cyl}$  is net produced pneumatic force due to the pressure difference in chambers  $a$  and  $b$  as shown in Fig.1.  $F_{ext}$  is the applied external force to pneumatic cylinder rod. In Eq.3,  $P_a, P_b$  are the pneumatic pressures in chambers.  $P_{atm}$  is the atmospheric pressure;  $A_a$  and  $A_b$  are chambers' effective areas where working pressure act on.  $A_{rod}$  is the cylinder rod cross sectional area that is namely  $(A_a - A_b)$  as shown in Fig.1. In this type of model, the friction between moving mass and the ground surface is eliminated by using rollers supporting  $M_e$ . It should also be kept in mind that any type of friction force is opposite to the motion direction. For the objective of this study, both external force and net produced cylinder force is assumed to be in the direction of motion.

$$F_{net} = F_{cyl} - F_f + F_{ext} = M * \ddot{x} \tag{2}$$

$$F_{cyl} = P_a * A_a - P_b * A_b - P_{atm} * A_{rod} \tag{3}$$

Friction force model used in this study is shown in Fig.2 and denoted by  $F_f$ . The combined Coulomb-viscous friction model is given by Eq.4. In this notation,  $F_c$  is the Coulomb friction force at the onset of piston motion and  $B$  denotes viscous friction coefficient which is related with the pneumatic cylinder speed,  $\dot{x}$ .

$$F_f = F_c + B * \dot{x} \tag{4}$$

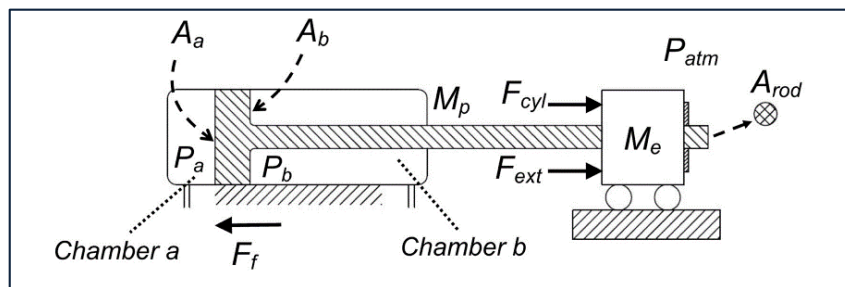


Figure 1. Standard pneumatic cylinder and its parameters

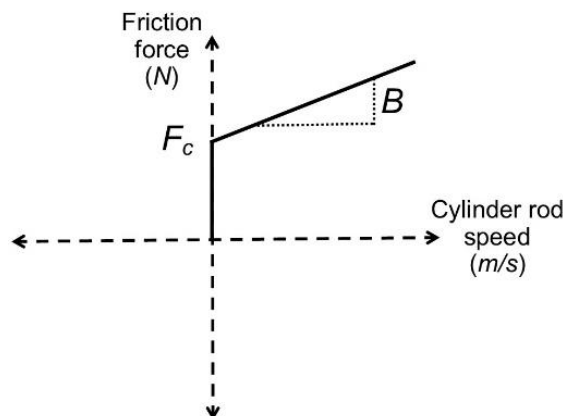


Figure 2. Combined Coulomb-viscous friction model curve

2.2. Proposed Method

The proposed method in this study includes applying an external force to the cylinder rod and in result measuring the sensory outputs as in the form of position ( $x$ ) and force applied ( $F_{ext}$ ) under the conditions where both chambers are open to atmosphere ( $P_a = P_b = P_{atm}$ ). Hence,  $F_{cyl}$  becomes zero in Eq.3. The experiments took place at constant speeds ( $\dot{x} = 0$ ) and there is no payload mass existing on the system ( $M_e = 0$ ). According to these criteria, Eq.2 and Eq.3 are rearranged and combined together as in the form of Eq.5 that is going to be studied.

$$F_{ext} = F_c + B * \dot{x} \tag{5}$$

In order to take advantage of Eq.5, cylinder rod should be set to motion in different speed levels by applying varying external load  $F_{ext}$  which can be either known weights or known user force applied externally. In this study, user applied external force is utilized since the experiments take place in horizontal plane.

The proposed method in this study has following two steps:

- The first step is to estimate Coulomb friction force ( $F_c$ ) value by applying an increasing external force ( $F_{ext}$ ) until the piston starts motion. The threshold force value would be  $F_{ext} = F_c$  based on Eq.5 since both speed and acceleration are zero.
- The second step is to estimate the viscous friction coefficient ( $B$ ) by applying a force such that the piston moves at a constant speed. Hence, based on Eq.5, acceleration of piston would be zero and viscous friction coefficient can be calculated directly by using  $F_c$  value found in the previous step with Eq.5.

### 2.3. Experimental Setup and Measurement Technique

Experimental setup includes, a basic pneumatic system. This system setup includes a double acting pneumatic cylinder, two speed control valves, one 5/3 directional control valve and air preparation unit, a load cell, a load cell amplifier, a linear potentiometer to measure linear position, two microcontroller boards (Arduino) and a PC for power source as well as serial output of measured variables ( $x$  and  $F_{ext}$ ) to the screen. The equipment used in this study is shown in Fig.3 and listed in detail in Table 1. Both input and output port of the actuator are opened to atmosphere. Even, no pneumatic pressures are applied to the chambers, a full pneumatic system is constructed for proposed experiments. Therefore, pneumatic actuator can be easily driven with an external force  $F_{ext}$  applied to its rod tip by any user.

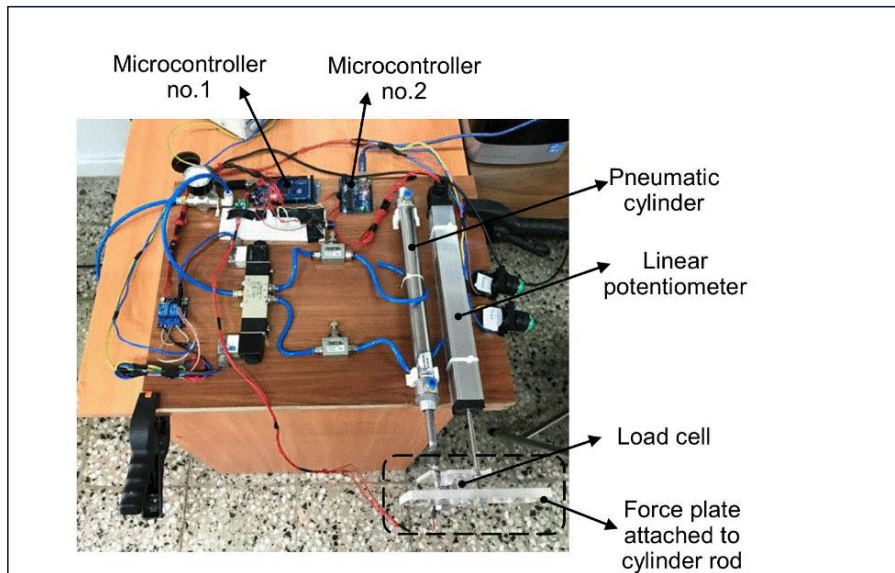


Figure 3. Experimental setup

Table 1. Experimental setup specifications

<b>Pneumatic cylinder</b>	250 mm stroke 25 mm piston diameter Double acting pneumatic cylinder
<b>Linear potentiometer</b>	250 mm stroke 0.01 mm resolution 0-5 V analogue output
<b>Load cell</b>	0-10 kg capacity 0-5 V analogue output
<b>Load Cell amplifier</b>	1.6 mA 2.6-5.5 V output
<b>Microcontroller</b>	Microcontroller no.1-Arduino Mega Microcontroller no.2-Arduino Uno
<b>PC</b>	64bit 2400 CPU 3.10 GHz processor

In this study, a plate joining cylinder and potentiometer is constructed to join the cylinder rod and linear potentiometer together. (Fig.4a). Load cell is then connected to this plate in a special way. There are two intermediate plates to direct external force correctly. (Fig.4b).

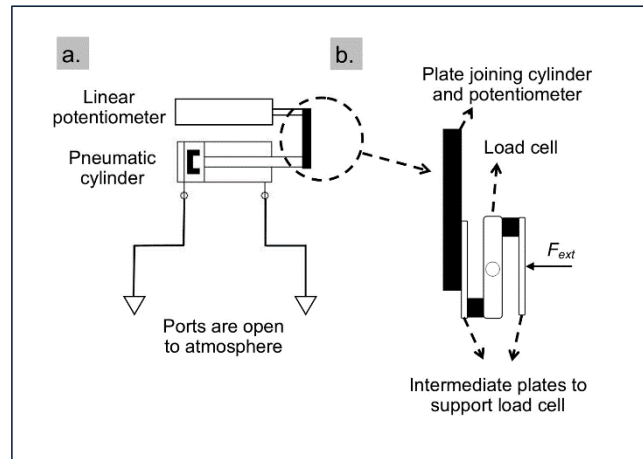


Figure 4. Load cell configuration

Two Arduino microcontrollers are used in the name of Microcontroller no.1 and Microcontroller no.2 shown in Fig.5. Microcontroller no.1 is used for force measurements only. Load cell is connected to this Arduino via a load cell amplifier. Force measurements are monitored via Arduino serial monitoring screen on PC with Arduino IDE interface. On the other hand, Microcontroller no.2 is used for kinematic measurements (position and velocity). This Arduino is connected to the MATLAB Simulink. A proper block diagram is constructed and position measurements are recorded. Velocity of the cylinder rod is derived from the first derivative of the position data as shown by MATLAB block diagram in Fig.6. Gain defines a conversion coefficient which is used to convert Analogue output 0-5 V of linear potentiometer to displacement value of pneumatic cylinder (0-250 mm). It is simply calculated as  $250/1024=0.2441$ .

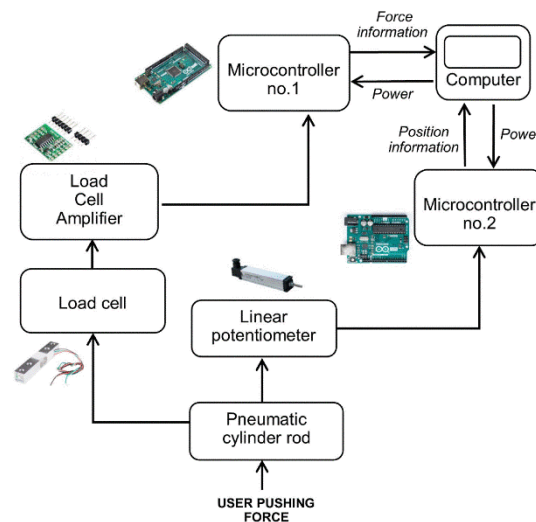


Figure 5. Experimental setup details and electronic system chart

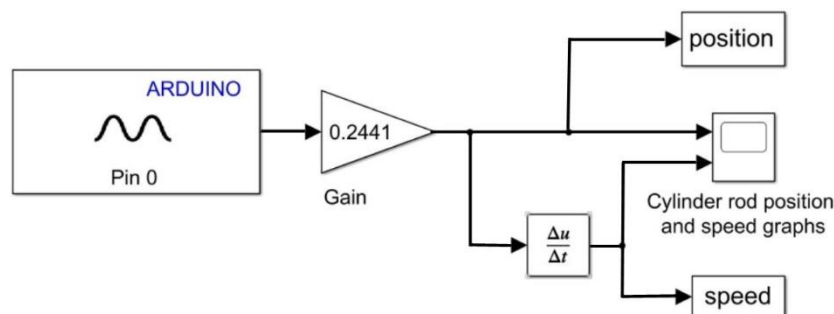


Figure 6. MATLAB Simulink block diagram for measurement of kinematic data

Experiments took place in both motion direction of cylinder rod i.e. extension motion (position from 0 to 250 mm) and retraction motion (from 250 to 0 mm). To be able to measure the applied external forces in both extension and retraction motions, the load cell has to be configured in two different modes. In the extension mode, the load cell is assembled on the right side of the joining plate (Fig.7a) whereas in the retraction mode it is assembled on the left side (Fig.7b).

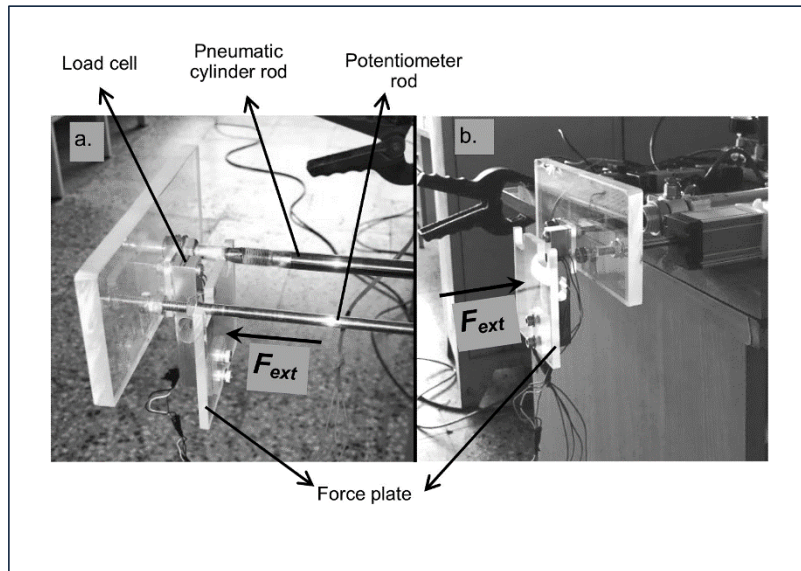


Figure 7. Force plate location according to the movement direction. (a. Extension mode, b. Retraction mode)

### 3. Experimental Results

The Coulomb friction force ( $F_c$ ) and viscous friction coefficient ( $B$ ) are evaluated for both extension and retraction modes of a pneumatic cylinder. In the evaluation of extension Coulomb friction force estimation, first the rod is fully retracted, i.e.  $x=0$  mm. Then, the rod is pushed gradually until it starts motion. The application of the force is stopped and the applied force data ( $F_{ext}$ ) at the onset of motion is read from the screen and recorded. This process is repeated through the stroke length at twelve different positions until the cylinder rod is fully extended, i.e.  $x=250$  mm. Each experiment is repeated ten times for the extension mode. Results are tabulated in Table 2. "C1" correspond to the first pneumatic cylinder evaluated in proposed setup.

On the other hand, the Coulomb friction force of the retraction mode is evaluated similarly. However, for this mode, the rod is fully extended, i.e.  $x=250$  mm, at the beginning of each experiment. Then, the rod is pushed for retraction gradually until the motion starts. The threshold force value is recorded immediately. This process is repeated twelve times in one retraction phase and these experiments are repeated for ten times for the retraction mode. Results are tabulated in Table 3.

Table 2.  $F_c$  Values- Extension mode-C1

Step	Experiment #									
	1	2	3	4	5	6	7	8	9	10
1	6.082	5.562	9.565	8.025	6.494	9.506	8.623	4.777	5.621	6.259
2	6.396	3.051	5.758	6.033	6.043	6.455	4.885	4.120	4.709	4.660
3	5.739	4.866	4.110	5.768	4.836	4.748	6.004	4.365	5.278	4.248
4	6.004	3.061	5.513	5.798	4.464	5.817	4.415	6.278	5.278	6.357
5	7.848	6.298	4.091	5.013	6.455	4.346	4.513	4.934	4.061	3.836
6	4.670	4.719	6.288	5.346	6.288	5.876	4.621	5.023	5.631	6.249
7	6.916	6.092	5.651	7.770	4.611	5.091	6.563	4.140	8.368	3.306
8	5.474	5.376	4.424	4.807	3.326	5.003	5.552	4.817	7.828	4.827
9	5.739	5.562	5.023	5.278	5.494	6.161	4.591	5.376	5.003	4.630
10	4.150	5.415	4.503	5.317	3.031	5.258	4.983	5.337	5.111	3.924
11	6.563	3.757	8.603	5.327	5.827	5.866	5.072	4.846	5.631	6.789
12	6.651	7.416	7.191	5.052	5.454	5.729	4.493	5.955	5.474	5.160
$\bar{F}_c$ (N)	6.019	5.098	5.893	5.794	5.194	5.821	5.360	4.997	5.666	5.020
	5.486									

**Table 3.**  $F_c$  Values- Retraction mode-C1

Step	Experiment #									
	1	2	3	4	5	6	7	8	9	10
1	4.581	9.153	6.347	9.692	6.043	6.151	8.299	7.858	5.160	7.338
2	4.042	3.934	4.944	3.434	4.807	4.679	5.464	3.257	7.024	4.326
3	5.131	4.934	7.720	4.807	3.483	6.043	4.709	6.190	4.199	4.365
4	6.170	3.286	6.014	4.267	4.228	5.337	5.611	4.885	4.974	4.699
5	5.621	6.161	4.974	3.846	6.739	5.513	5.454	2.943	5.091	4.797
6	5.915	4.218	9.535	4.670	5.415	6.033	5.258	3.747	4.130	5.003
7	5.847	6.671	5.180	6.789	5.827	4.464	5.150	5.758	3.365	4.777
8	5.052	4.807	5.857	4.866	7.720	5.150	5.994	5.700	3.326	5.994
9	5.003	4.002	4.336	4.807	6.514	5.935	5.749	5.484	4.660	6.416
10	3.885	5.101	5.052	6.416	4.385	6.259	5.660	5.189	4.562	6.347
11	7.877	3.934	4.630	4.827	4.454	5.425	5.729	3.895	5.189	4.827
12	2.649	6.102	4.130	3.355	5.239	3.983	6.308	5.131	5.611	4.326
$\bar{F}_c$ (N)	5.148	5.192	5.727	5.148	5.404	5.414	5.782	5.003	4.774	5.268
	5.286									

After the evaluation of Coulomb friction force values the viscous friction coefficient ( $B$ ) can be evaluated as follows: For extension mode, cylinder rod is retracted fully. An external force is applied for extension to the force plate (Fig.7a) at constant speed through the full stroke. Applied load  $F_{ext}$  is recorded as well as the average constant speed  $\dot{x}$  as shown in Simulink screen (Fig.8). These results are substituted into Eq.5 together with previously obtained Coulomb friction force value for extension mode (average result from Table 2). The corresponding viscous friction coefficient  $B$  can be easily calculated. This experiment is repeated for ten times. For the retraction mode, the same procedures are applied except that the cylinder rod is fully extended at the beginning. An external force is applied for retraction (Fig.7b) at constant speed through the full retraction stroke. By identifying the applied external force and the average constant speed, the viscous friction coefficient can be calculated by Eq.5 for the retraction mode. This experiment is also repeated ten times for the retraction mode. Experimental results are shown in Table 4 and 5 for extension and retraction modes of cylinder 1, respectively.

**Table 4.**  $B$  values- Extension mode-C1

Experiment #	$F_{ext}$ (N)	$\dot{x}$ (m/s)	$B$ (Ns/m)	$\bar{B}$ (Ns/m)
1	17.650	0.115	105.771	103.428
2	15.941	0.110	95.043	
3	16.400	0.122	89.237	
4	16.260	0.119	90.535	
5	16.980	0.101	113.799	
6	17.690	0.114	107.050	
7	19.610	0.120	118.150	
8	16.260	0.111	97.060	
9	18.060	0.107	117.511	
10	16.100	0.106	100.129	

**Table 5.**  $B$  values- Retraction mode-C1

Experiment #	$F_{ext}$ (N)	$\dot{x}$ (m/s)	$B$ (Ns/m)	$\bar{B}$ (Ns/m)
1	18.690	0.138	97.13	84.914
2	17.010	0.119	98.521	
3	15.940	0.111	95.982	
4	14.060	0.089	98.033	
5	17.570	0.168	73.119	
6	18.790	0.184	73.391	
7	17.000	0.198	59.161	
8	15.850	0.121	87.305	
9	19.160	0.173	80.196	
10	16.160	0.126	86.301	

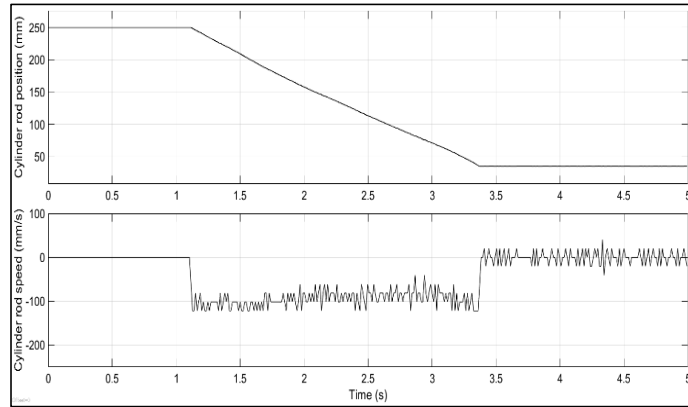


Figure 8. MATLAB Simulink kinematic data measurement screen (retraction mode)

Results of the experiments and calculation show that there is almost no difference between the Coulomb friction force values ( $F_c$ ) of extension and retraction modes. However, in the estimation of viscous friction coefficient ( $B$ ), it is obvious that, retraction mode friction coefficient value is lower than extension mode. To verify this situation, the same experiments are conducted on the same experimental setup with a different linear pneumatic cylinder in the name of cylinder 2 (C2) (double acting type, 300mm stroke and 25mm bore diameter). The values of Coulomb friction force and viscous friction coefficient for the corresponding modes are tabulated in Table 6 and 7, respectively. The results of the second pneumatic cylinder (C2) proved that the Coulomb friction force values are approximately same for both extension and retraction modes. Also, the viscous friction coefficient varies considerably for both extension and retraction.

Table 6.  $F_c$  Values- C2 (\* values in each row show the average of 12 values through cylinder stroke)

Experiment #	Extension* mode (N)	Retraction* mode (N)
1	6.864	7.586
2	6.105	6.020
3	6.194	6.508
4	5.774	6.636
5	7.082	6.828
6	6.207	6.412
7	6.875	7.452
8	6.663	6.258
9	6.114	6.058
10	6.503	7.217
$\bar{F}_c$ (N)	6.446	6.692

Table 7.  $B$  values-C2 (\*values in each row is calculated using Eq.5 with measured  $\dot{x}$  and  $F_{ext}$ )

Experiment #	Extension* mode (Ns/m)	Retraction* mode (Ns/m)
1	51.740	50.400
2	45.270	44.707
3	56.530	47.142
4	40.500	42.690
5	44.940	46.650
6	46.920	43.800
7	47.690	53.070
8	44.200	43.930
9	48.570	40.060
10	50.450	41.430
$\bar{B}$ (Ns/m)	47.681	45.387

The statistical analysis of the collected experimental data has been carried out for 95% confidence interval of the “student-t” distribution. The results are tabulated in Table 8. From Table 8, static Coulomb friction force ( $F_c$ ) has a standard deviation value closer to 1 (for both extension and retraction) and therefore it results a narrow confidence interval. However, the standard deviation for the viscous friction coefficient rises to the values of 13 for the “cylinder 1” and 4 for the “cylinder 2” which is due to the small number of experiments. However, as a



general method, the results prove that the friction parameters can be estimated with sufficient accuracy with increasing the number of experiments.

**Table 8.** 95% confidence intervals for the friction parameters of the tested pneumatic cylinders

Parameters	Standard deviation	Lower limit	Upper limit
Pneumatic cylinder 1- (C1) results			
$F_c$ – (extension) (N)	1.225	5.265	5.708
$F_c$ – (retraction) (N)	1.275	5.056	5.516
$B$ – (extension) (Ns/m)	10.701	95.774	111.083
$B$ – (retraction) (Ns/m)	13.308	75.395	94.433
Pneumatic cylinder 2- (C2) results			
$F_c$ – (extension) (N)	1.605	6.156	6.736
$F_c$ – (retraction) (N)	2.216	6.292	7.093
$B$ – (extension) (Ns/m)	4.482	44.475	50.887
$B$ – (retraction) (Ns/m)	3.811	42.662	48.114

#### 4. Discussion and Conclusion

In this study, a simple and cheap experimental method has been developed for estimating two unique nonlinear parameters of a particular linear pneumatic cylinder. They are Coulomb friction force,  $F_c$  and viscous friction coefficient,  $B$ . Only a load cell and a linear potentiometer were used as sensors. Cheap and readily available microcontroller Arduino was utilized with a main computer for data measurement and recording.

In this study, two linear pneumatic cylinders have been evaluated with the same experimental setup and same approach to show the effectiveness of proposed method. The parameters have been successfully calculated after a set of experiments. From the obtained results it is clear that pneumatic cylinder 1 (C1) has good and consistent Coulomb friction force  $F_c$  results, but relatively inconsistent viscous friction coefficient  $B$  results. On the other hand, in the examination of pneumatic cylinder 2 (C2), it is very obvious that the results are very promising. Friction force ( $F_c$ ) values and viscous friction coefficients ( $B$ ) are very consistent. However, some viscous friction coefficient ( $B$ ) values for C1 and C2 look like an outlier and not consistent at some speed levels, for both of extension and retraction modes. The reason behind that was probably the precision of load cell and some experimental rig errors. If a more precise load cell is used more consistent results can be obtained from this proposed method.

As a conclusion, in this study it has been verified that linear pneumatic cylinders have nearly similar Coulomb friction force ( $F_c$ ) values in both extension and retraction modes, however they can have different viscous friction coefficients  $B$  in two different motion modes. Knowing these parameters would help precisely develop the dynamic model of a pneumatic cylinder and then the developed dynamic model can be used for any other control applications of pneumatic actuators.

#### Acknowledgement

This project was funded by Çukurova University-ÖYP Coordination.

#### Conflict of Interest

No conflict of interest was declared by the authors.

#### References

Al-Bender, F., Lampaert, V., & Swevers, J., 2005. The generalized Maxwell-slip model: A novel model for friction simulation and compensation. IEEE Transactions on Automatic Control, 50(11), 1883–1887. <https://doi.org/10.1109/TAC.2005.858676>

- Andrighetto, P. L., Valdiero, A. C., & Carlotto, L., 2006. Study of the friction behavior in industrial pneumatic actuators. *ABCM Symposium Series in Mechatronics*, 2(2005), 369–376
- Belforte, G., D'Alfio, N., Raparelli, T., 1989. Experimental Analysis of Friction Forces in Pneumatic Cylinders. *The Journal of Fluid Control*, Vol.20, 42-60
- Chang, H., Lan, C. W., Chen, C. H., Tsung, T. T., & Guo, J. Bin., 2012. Measurement of frictional force characteristics of pneumatic cylinders under dry and lubricated conditions. *Przeglad Elektrotechniczny*, 88(7 B), 261–264
- Dağdelen, M., & Sarigeçli, M. İ., 2017. Development of a Conceptual Model for Wrist/Forearm Rehabilitation Robot with Two Degrees of Freedom. *Advances in Robot Design and Intelligent Control*, 523–530. <https://doi.org/10.1007/978-3-319-49058-8>
- DAHL, P. R., 1968. [19]-English: A Solid Friction Model (modèle Dahl). Technical Report, The Aerospace Corporation, El Segundo, 158
- De Wit, C. C., Olsson, H., Astrom, K. J., & Lischinsky, P., 1995. A New Model of Control Systems with Friction. *IEEE Transactions On Automatic Control*, 40(3), 419–425
- Dupont, P., Armstrong, B., & Hayward, V., 2000. Elasto-plastic friction model: Contact compliance and stiction. *Proceedings of the American Control Conference*, 2(June), 1072–1077. <https://doi.org/10.1109/acc.2000.876665>
- Földi, L., Beres, Z., Sarközi, E., 2011. Novel Cylinder Positioning System Realized by Using Solenoid Valves. *Sustainable Construction and Design*, 142-151
- Guenther, R., Perondi, E. C., Depieri, E. R., & Valdiero, A. C., 2006. Cascade controlled pneumatic positioning system with LuGre model based friction compensation. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 28(1), 48–57. <https://doi.org/10.1590/S1678-58782006000100006>
- Harris, P. G., O'Donnell, G. E., & Whelan, T., 2012. Modelling and identification of industrial pneumatic drive system. *International Journal of Advanced Manufacturing Technology*, 58(9–12), 1075–1086. <https://doi.org/10.1007/s00170-011-3447-7>
- Hejrati, B., & Najafi, F., 2013. Accurate pressure control of a pneumatic actuator with a novel pulse width modulation-sliding mode controller using a fast switching On/Off valve. *Proceedings of the Institution of Mechanical Engineers. Part I: Journal of Systems and Control Engineering*, 227(2), 230–242. <https://doi.org/10.1177/0959651812459303>
- Karnopp, D., 1985. Computer Simulation of Stick-Slip Friction in Mechanical Dynamic Systems. *ASME J. Dyn. Sys., Meas., Control* 107(March 1985), 100–103
- Korucu, S., Samtaş, G., & Soy, G., 2015. Design and Experimental Investigation of Pneumatic Movement Mechanism Supported by Mechanic Cam and Crank Shaft. *TEM Journal*, 4(1), 22–34
- Kosari, H., & Moosavian, S. A. A., 2015. Friction compensation in a pneumatic actuator using recursive least square algorithm. *2015 Australian Control Conference, AUCC 2015*, 81–86
- Lafmejani, A. S., Masouleh, M. T., & Kalhor, A., 2016. An experimental study on friction identification of a pneumatic actuator and dynamic modeling of a proportional valve. *4th RSI International Conference on Robotics and Mechatronics, ICRoM 2016*, 166–172. <https://doi.org/10.1109/ICRoM.2016.7886840>
- Liu, Y. F., Li, J., Zhang, Z. M., Hu, X. H., & Zhang, W. J., 2015. Experimental comparison of five friction models on the same test-bed of the micro stick-slip motion system. *Mechanical Sciences*, 6(1), 15–28. <https://doi.org/10.5194/ms-6-15-2015>
- Ritcher, R.R.M., Zamberian, C.V., Valdiero, A.C. & Rasia, L.A., 2014. Friction dynamics mathematical modelling in special pneumatic cylinder. *ABCM Symposium Series in Mechatronics*, vol.6, 800-808
- Saha, A., Wahi, P., Wiercigroch, M., & Stefański, A., 2016. A modified LuGre friction model for an accurate prediction of friction force in the pure sliding regime. *International Journal of Non-Linear Mechanics*, 80, 122–131. <https://doi.org/10.1016/j.ijnonlinmec.2015.08.013>
- Saleem, A., Wong, C. B., Pu, J., & Moore, P. R., 2009. Mixed-reality environment for frictional parameters identification in servo-pneumatic system. *Simulation Modelling Practice and Theory*, 17(10), 1575–1586. <https://doi.org/10.1016/j.simpat.2009.06.016>
- Swevers, J., Al-Bender, F., Ganseman, C. G., & Prajogo, T., 2000. An integrated friction model structure with improved presliding behavior for accurate friction compensation. *IEEE Transactions on Automatic Control*, 45(4), 675–686. <https://doi.org/10.1109/9.847103>
- Tran, X. B., & Yanada, H., 2013. Dynamic Friction Behaviors of Pneumatic Cylinders. *Intelligent Control and Automation*, 04(02), 180–190. <https://doi.org/10.4236/ica.2013.42022>
- Wang, J., Wang, J. D., Daw, N., Wu, Q. H., & Member, S., 2004. Identification of Pneumatic Cylinder Friction Parameters Using Genetic Algorithms. *IEEE/ASME Transactions on Mechatronics*, 9(1), 100–107