

Development of a Test Apparatus for Estimation of Friction Parameters at Linear Pneumatic Cylinders

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Abstract

Pneumatic cylinders possess non-linear characteristics due to the air-compressibility and stick-slip in cylinder barrel. Friction characteristics in pneumatic cylinders is one of the main non-linearity that negatively affects the precise control. To be able to use these actuator systems in high level control applications, their friction force models should be developed. Hence, unknown friction parameters should be estimated correctly since the friction parameters of pneumatic cylinders are not listed in the manufacturers' catalogue and these parameters cannot be calculated by only analytical methods. For that reason, in this study, a test apparatus is designed and experimental procedures are developed for the estimation of the friction parameters of linear pneumatic cylinders as in the form of static friction force, Coulomb friction force, Stribeck velocity and viscous damping coefficient.

Keywords: Friction force parameters, Pneumatic cylinder, Test apparatus

Lineer Pnömatik Silindirlerin Sürtünme Parametrelerinin Değerlendirilmesi için Bir Test Düzeneginin Geliştirilmesi

Öz

Pnömatik silindirler havanın sıkışabilirliğinden ve silindir bloğunda meydana gelen yapışma-kayma olaylarından dolayı lineer olmayan özelliklere sahiptirler. Pnömatik silindirlerdeki sürtünme karakteristiği hassas kontrol işlemlerini olumsuz yönde etkileyen lineer olmayan ana özelliktir. Bu tahrik sistemlerini yüksek seviye kontrol uygulamalarında kullanabilmek için, sürtünme kuvveti modellerinin geliştirilmesi gerekir. Pnömatik silindirlerin sürtünme parametreleri üretici kataloglarında belirtilmediğinden ve sadece analitik yollarla saptanamayacakları için bilinmeyen sürtünme parametrelerinin belirlenmesi gerekir. Bu sebepten dolayı, bu çalışmada, bir test düzenegi tasarlanmış ve pnömatik silindirlerin sürtünme parametrelerinin statik sürtünme kuvveti, Coulomb sürtünme kuvveti, Stribeck hızı ve viskoz sönümleme katsayısı formatında tahmin edilmesi için deneysel adımlar geliştirilmiştir.

Anahtar Kelimeler: Sürtünme kuvveti parametreleri, Pnömatik silindir, Test düzenegi

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1. INTRODUCTION

Pneumatic actuation systems are widely preferred, clean and soft actuation elements due to their remarkable properties of light weightness, high power to weight ratio, easy maintenance and low cost. However, these actuation systems have also nonlinearities and disadvantages due to the air compressibility and stick-slip phenomenon that takes place at the surfaces between cylinder barrel and piston seals. The friction forces affect the control performance of pneumatic cylinders and these forces are highlighted as the main non-linearity reason in the literature [1-5].

In industrial applications, pneumatic cylinders can directly be selected based on the required stroke (L) and bore diameter (D) since pneumatic systems are generally used for basic on-off control applications. However, in order to utilize these outstanding actuators in high level control applications, stroke length and bore diameter alone remain meaningless at this stage since dynamic characteristics as in the form of mass moment of inertia and friction force of any used actuator have a strong impact on the control process. Therefore, the aim of this study is to develop an experimental apparatus which is easy to use, cheaper and that can be used in obtaining the parameters of friction force at a particular pneumatic linear actuator.

The friction force model to be used in mechanical systems should be chosen based on the type of application and the level of required control. In general friction force models in the literature can be divided into two categories: model of gross sliding phenomenon or advanced model of sliding phenomenon. For the models of the gross sliding phenomenon in friction, Coulomb model [6,7], combined Coulomb-Viscous model [8] and combined Static-Stribeck-Coulomb-Viscous friction model [9,10] can be listed. In addition to these standard friction models, more advanced friction models as LuGre model [11], modified LuGre model [12,13], Dahl model [14], Elastoplastic model [15], Leuven model [16], Karnopp model [17], Generalized Maxwell Slip model [18] which also take into account pre-sliding phenomenon can be shown. Hence, the models in the second category are very

complex models and include many parameters to be defined clearly. If a pneumatic actuator is utilized in medium to high speeds, there is no need to use these complex friction models. The models in the first category are pretty satisfactory which is also the focus of this study.

In the literature, the basic equation of friction force for pneumatic cylinders is given as (Eq. 1).

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

However, this mathematical expression is too simple and far from defining the requisite precise dynamic model. In this equation, μ is the friction coefficient (ranges between 0.02 and 0.20 as stated in [2]), P is the pneumatic working pressure and A is the piston effective area.

In the literature, there are various types of experimental studies for identifying friction parameters of pneumatic cylinders. Schroeder et al. [19] proposed an experimental method for evaluating several empirical and semi-empirical friction force models. By gathering experimental data, they chose the friction model which suited best to the pneumatic friction with minimum amount of error. Belforte et al. [20] developed an experimental setup to evaluate the friction force in pneumatic cylinders under varying operating conditions (i.e. working pressure, piston speed and bore diameter of cylinder). However, their setup includes complicated and expensive equipment including hydraulic circuit elements to produce required force and speed on pneumatic cylinder motion. Wang et al. [1] suggested a combination of experimental and analytical method by using Genetic Algorithm (GA) for predicting the friction parameters as in the form of static friction, Coulomb friction and viscous coefficient. They carried out the experiments for both directions of movement in pneumatic cylinders and estimated the average friction force values. In addition to these studies, combined Static-Coulomb-Stribeck-Viscous friction model was intended to be used by Andrighetto et al. [2]. In that study, two different kinds of experimental setup were constructed and eight pneumatic cylinders having different stroke length and bore diameter were examined. The

friction force parameters were tabulated with the help of curve fitting programs. A simple and cheap experimental setup which was manually operated for determining only coulomb friction force and viscous damping coefficient was proposed in [21].

Tran et al. [22] developed an experimental setup based on their own modified LuGre friction model for investigating the dynamic friction behaviors of pneumatic cylinders at low and high speed with varying working pressures. Their setup includes hydraulic elements as in Belforte et al. [18]. Ritcher et al. [23] proposed improved LuGre model for the estimation of friction parameters with the help of “nlinfit” function from MATLAB software. Kosari et al. [3] proposed RLS algorithm to estimate friction force parameters. Lafmejani et al. [4], proposed the friction force parameters in the form of exponential, polynomial and Fourier series transform functions.

Another interesting solution was proposed by Saleem et al. [5] by utilizing mixed-reality environment technique. The proposed algorithm consisted of both real and virtual environments. The data were taken from the real environment (experimental setup) and fed into the virtual environment to estimate friction parameters.

The currently available experimental methods in the literature for the estimation of friction force parameters in a pneumatic cylinder have generally complex and expensive equipment where it is either difficult to collect correct data or it is time consuming process to obtain the required parameters. Hence, in this study, an efficient and cheap experimental setup with minimum number of elements are developed. In order to retrieve correct instant data to a computer, the experimental setup consists of a control card, servo control valve and two-way relay as well as the necessary sensors as in the form of linear potentiometer and pressure sensors.

2. MATERIAL AND METHOD

In this study, the friction force in pneumatic cylinder is based on the combined Static-

Coulomb-Stribeck-Viscous friction model [9,10] as given in (Eq. 2) and illustrated in Figure 1:

$$F_f = F_c + (F_s - F_c) * e^{-\left(\frac{\dot{x}}{\dot{x}_s}\right)^j} + B * \dot{x} \quad (2)$$

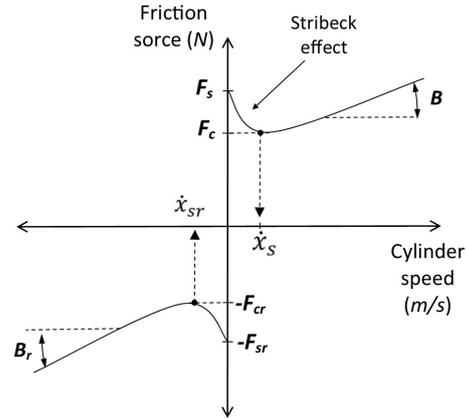


Figure 1. Combined Static-Coulomb-Stribeck-Viscous friction model

In this model (Eq. 2), F_f is the friction force; F_c is the coulomb friction force; F_s is the maximum static friction force for impending motion; \dot{x}_s is the Stribeck velocity showing the Stribeck effect on static friction and Coulomb friction; and B is the viscous friction coefficient in extension motion of piston rod. For retraction motion analysis, “r” index is added to the subscripts (as F_{sr} , F_{cr} , \dot{x}_{sr} and B_r , respectively) since these values can be different for two motion directions. In Eq. 2, j is a constant which assumes a value between 0.5 and 2. [2].

A schematic representation of a pneumatic cylinder and forces acting on the system together with other related parameters are shown in Figure 2. In the figure, pressures and effective areas in “chamber a” and “chamber b” are represented clearly. External mass M_e is shown for the generalization of the procedures. The mass (M_p) and cross-sectional area (A_p) of the piston rod are also identified.

In order to determine the parameters of Eq. 2, Newton’s second law is utilized for the net force (F_{net}) acting on the system as stated in Eq. 3:

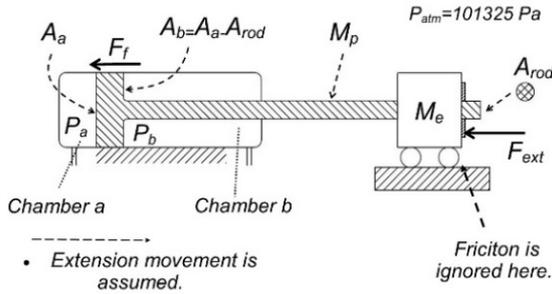


Figure 2. Symbolic representation of a pneumatic cylinder and related parameters

$$F_{net} = M \ddot{x} \quad (3)$$

In the right side of Eq. 3, M is the sum of moving masses (i.e. piston-rod mass (M_p) and payload mass (M_e)) but in our study there is no external mass. In the proposed method, the system is run at constant speed values in each experiment which results that net forces should be equal to zero. On the other hand, the net force of Eq. 3 can be restated as in Eq. 4:

$$F_{net} = F_{cyl} - F_f + F_{ext} \quad (4)$$

In this equation, F_{ext} is the applied external force to pneumatic cylinder rod and it is zero for the proposed method ($F_{ext} = 0$). F_{cyl} is the net produced pneumatic force due to the pressure difference in “chamber a” and “chamber b” as defined in Eq. 5:

$$F_{cyl} = P_a \cdot A_a - P_b \cdot A_b - P_{atm} \cdot A_{rod} \quad (5)$$

In Eq. 5, P_a and P_b correspond to the absolute pressure in “chamber a” and “chamber b”, respectively. A_a and A_b are the net pressure acting areas in respective chambers as shown in Figure 2. P_{atm} is the atmospheric pressure that act on the cross-sectional area (A_{rod}) of the cylinder rod.

Finally, from Eqs. 3 and 4 with zero acceleration and no external load, it can be easily concluded that F_{cyl} should be equal to the friction force. By rearranging the equations, the friction force definition can be restated as in Eq. 6:

$$F_f = P_a \cdot A_a - P_b \cdot A_b - P_{atm} \cdot A_{rod} \quad (6)$$

3. EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUE

Experimental setup consists of a pneumatic system and an electronic system for data acquisition and control. These two systems will be discussed separately. The pneumatic system (shown in Figure 3) includes (i.) an air source compressor, (ii.) a manually adjustable pressure valve, (iii.) a 5/3 open center special pneumatic directional control valve, (iv.-v.) two one-way air flow control valves, (vi.) a linear standard pneumatic cylinder.

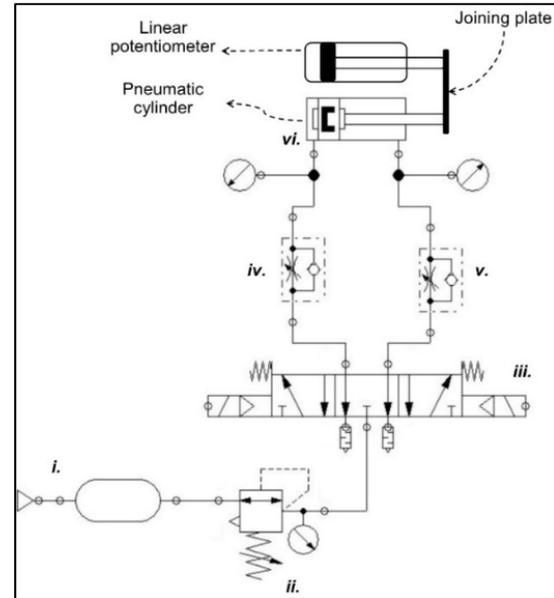


Figure 3. Schematic representation of pneumatic system

On the other hand, the electronic system (shown in Figure 4) consists of two Arduino microcontroller cards, a linear potentiometer for position measurement, two analogue output pressure sensors for reading pressure values in chambers, a relay card to control directional control valve and two buttons to move pneumatic cylinder in the required movement directions. Microcontroller no.1 is responsible for only the movement control of pneumatic cylinder. For this reason, a push button for extension and another push button for retraction movement of the pneumatic cylinder are connected to this microcontroller. Microcontroller

no.2 is utilized for data recording during experiments. Linear potentiometer reads the position data of the piston rod. The two pressure sensors at the inlet and outlet ports of the pneumatic cylinder are also connected to this microcontroller card. Hence, all the collected data

(position & pressure) are sent to computer to be processed in MATLAB Simulink software. The whole experimental setup is also shown in Figure 5.

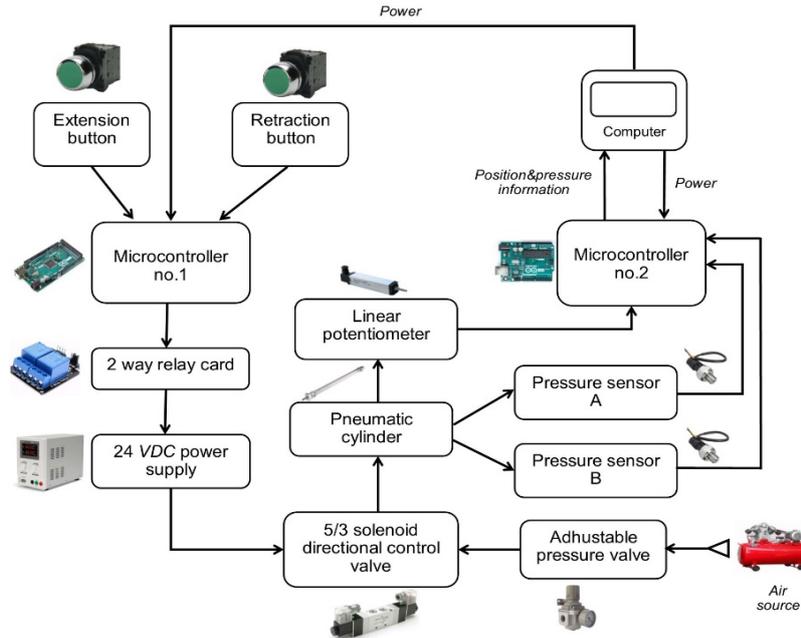


Figure 4. Complete system block representation

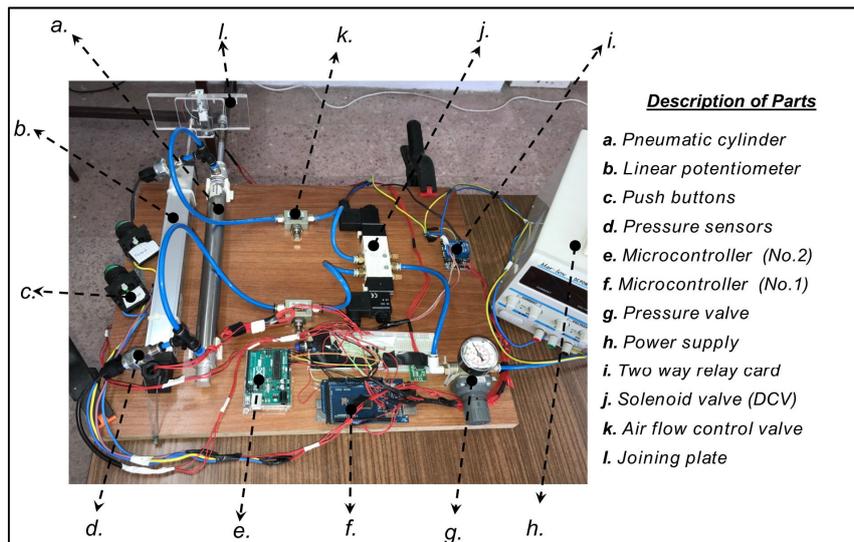


Figure 5. Experimental setup

The collected data from each experiment are evaluated in MATLAB Simulink. Hence, a block diagram (shown in Figure 6) is developed for the processing of the collected data. According to the block diagram, chamber pressures and piston rod position data are inputs. First, the piston speed is derived from the position data and the friction force value is calculated with respect to Eq. 6 as outputs.

4. PROCEDURES OF EXPERIMENTS

The identification of parameters in Eq. 2 requires two sets of experiments. In the first experiment set, the maximum static friction (F_s) has to be determined. In the second set, the friction force (F_f) values should be determined for various speeds of piston rod. Then, a curve fitting can be applied to precisely determine the unknown parameters.

4.1. Procedures for the First Experiment

The following procedures are developed for identification of static friction force in extension and retraction movements of a pneumatic cylinder.

1. Both air flow control valves are set to fully open.
2. Pressure control valve is set to 0 bar gauge pressure.
3. Extension button is pushed and hold in that position.
4. The air pressure is gradually increased from the pressure control valve.
5. As soon as a motion is observed from the screen, the experiment is stopped.
6. The maximum net force value which corresponds to the static friction value in extension movement direction is recorded from the screen.
7. Experiments should be repeated at least 15 times.

An example experiment output is illustrated in Figure 7 for clarification of the procedures. It should also be noted that the retraction experiments have exactly the same procedures

except that in the third step the retraction button should be pushed.

4.2. Procedures for the Second Experiment

The following procedures are developed for identification of friction force values under various speeds in extension and retraction movements of a pneumatic cylinder.

1. The pressure regulating valve is set to 5 bar.
2. The air flow control valves are adjusted to certain positions creating a specific constant piston speed.
3. Extension button is pushed and hold in that position.
4. The pneumatic cylinder is extended till end position at a constant speed.
5. The position and pressure data are collected.
6. The average of the net force from start to end of piston motion is recorded as net force. An example experiment output for net force is shown in Figure 8.
7. The average of the piston speed from start to end of piston motion is recorded as constant speed. An example experiment output for piston speed is shown in Figure 9.
8. The net force (F_f) and corresponding constant speed values are recorded.
9. Experiments should be repeated at least 15 times.

It should be reminded that the retraction experiments have exactly the same procedures except that in the third step the retraction button should be pushed.

5. EXPERIMENTAL RESULTS

The developed procedures are applied on an available pneumatic cylinder for the identification of its friction force model. The technical specifications of used linear pneumatic cylinder, linear potentiometer, pressure sensors, pressure regulating valve, microcontrollers and PC are tabulated in Table 1. By following the first set of procedures, static friction force for both extension and retraction movements (F_s and F_{sr} , respectively) are determined for

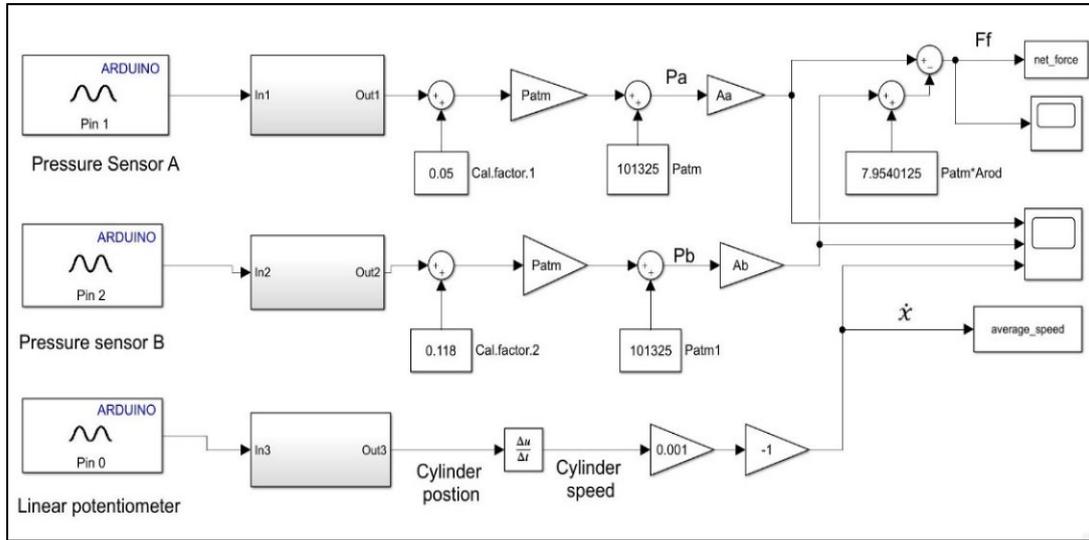


Figure 6. MATLAB Simulink block diagram

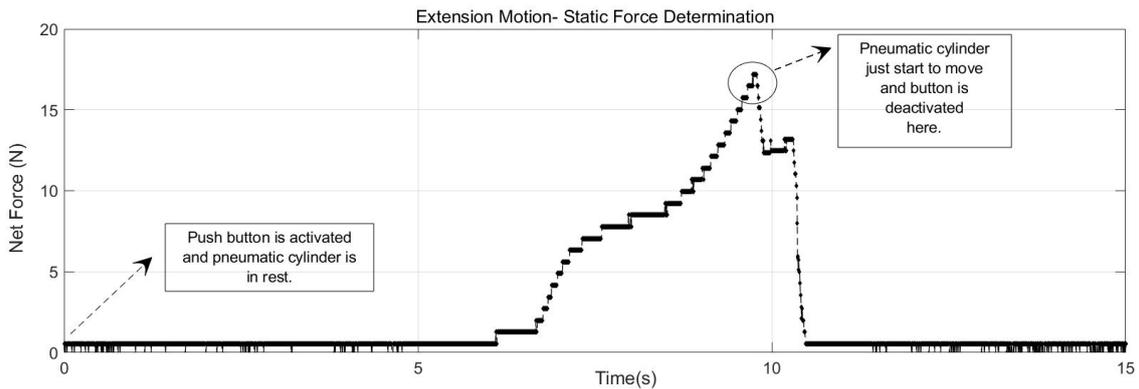


Figure 7. MATLAB Simulink net force output for first experiment

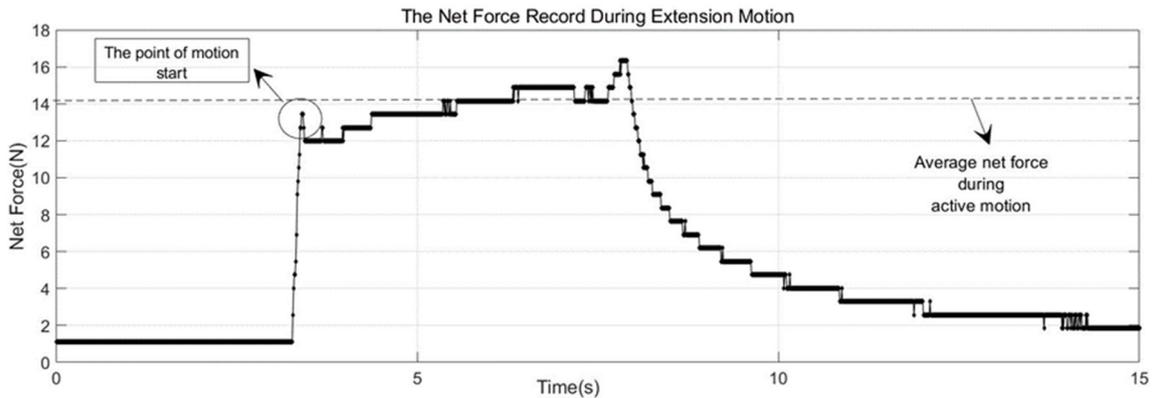


Figure 8. MATLAB Simulink net force output for second experiment

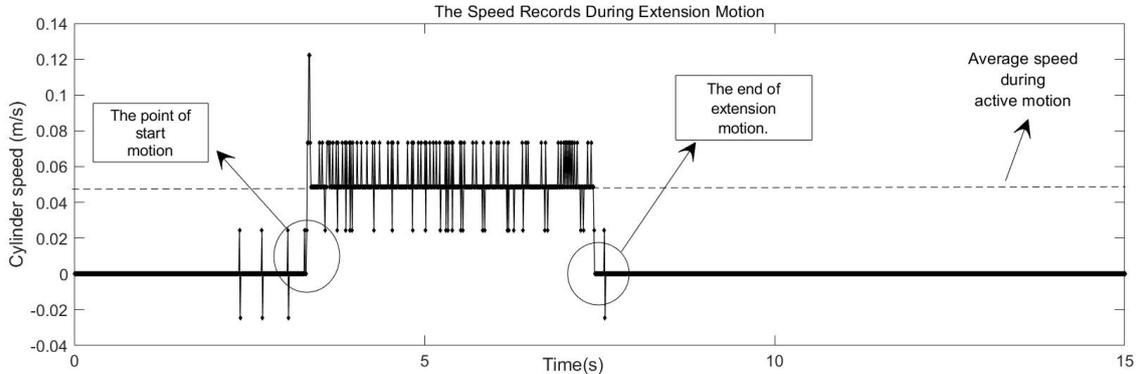


Figure 9. MATLAB Simulink speed output for second experiment

fifteen times as listed in Table 2. From the second set of procedures, friction force values for extension movement are obtained for various piston speeds and tabulated in Table 3. The same experiments are repeated for retraction movement and the corresponding values are given in Table 4.

The static friction force values (F_s) in Eq. 2 for extension and retraction are found by averaging the fifteen values in Table 2 as shown in the last row. These values are recorded as $F_s = 13.35\text{ N}$ and $F_{sr} = -11.08\text{ N}$. Then, a curve fitting operation is applied by utilizing the values in Table 3 for extension movement for obtaining the other parameters of Eq. 2 and the results are represented in Figure 10. Therefore, F_c , \dot{x}_s and the viscous friction coefficient are calculated as 8.6560 N , 0.001 m/s and 16.290 Ns/m , respectively, for extension. On the other hand, the result for retraction movements slightly differed from extension type one. By utilizing the values in Table 4 and applying a curve fitting operation, the parameters of friction force for retraction movement is obtained (Figure 10) as follows: $F_{cr} = -4.670\text{ N}$, $\dot{x}_{sr} = -0.032\text{ m/s}$ and the viscous damping coefficient is 35.590 Ns/m .

6. DISCUSSION AND CONCLUSION

The aim of this study is to present a test apparatus for obtaining friction force parameters of linear pneumatic cylinders whose stroke lengths are up to 250 mm (that is restricted by the linear potentiometer capability). The friction

Table 1. Specifications of equipment used in experiments

Experimental Setup Specifications	
Linear Pneumatic Cylinder	$L = 250\text{ mm}$ stroke $D = 25\text{ mm}$ piston diameter $D_{rod} = 10\text{ mm}$ rod diameter Double acting $A_a = 0.000490625\text{ m}^2$ $A_b = 0.00041212\text{ m}^2$ $A_{rod} = 0.0000785\text{ m}^2$
Linear Potentiometer	250 mm stroke 0.01 mm resolution $0-5\text{ VDC}$ analogue output
Pressure Sensors	$0-1.2\text{ MPa}$ measuring capacity $0-5\text{ VDC}$ analogue output Well compatible with Arduino microcontrollers
Pressure Regulating Valve	Max. input pressure = 16 bar Output pressure range = $0.5-10\text{ bar}$ Max. working temperature = 50°C Manually adjustable
Micro-controllers	Microcontroller no.1-Arduino Mega Microcontroller no.2-Arduino Uno
PC	64bit 2400 CPU 3.10Ghz processor

Table 2. Measurement of F_s and F_{sr}

Experiment no	Measured F_s (N)	Measured F_{sr} (N)
1	12.85	-11.58
2	14.90	-10.31
3	14.90	-12.37
4	12.01	-11.03
5	12.73	-12.02
6	12.73	-11.53
7	13.31	-9.82
8	13.20	-12.37
9	12.47	-11.03
10	13.80	-12.37
11	12.47	-10.43
12	14.39	-11.64
13	14.04	-9.93
14	14.04	-9.82
15	12.47	-9.93
Average	13.35	-11.082

force model is based on the combined Static-Coulomb-Stribeck-Viscous friction model. The proposed test apparatus consists of low cost equipment for pneumatic cylinders, low cost sensors and MATLAB software to get the required data and obtain friction parameters easily. The results show very good convergence in the calculation of static friction force (F_s and F_{sr}). Also, the Stribeck effect is observed easily with this proposed setup and from experimental result.

As a conclusion of this study, the friction in pneumatic cylinders cannot be assumed constant and it is shown that they vary with piston speed. Hence, a detailed friction model could be used easily in precise control applications of pneumatic cylinders. It would be also used as a guide for the selection of a pneumatic cylinder for a particular application based on the control requirements. As a future study, the investigation of friction force values through whole stroke length as well as evaluation of friction force under varying operating pressure, bore diameter and lubrication conditions should be performed.

Table 3. Measurement of average speed and friction force - Extension movement

Experiment no	Average Speed (m/s)	Measured F_f (N)
1	0.0091	8.6562
2	0.0230	9.6773
3	0.0289	11.8275
4	0.0515	13.6755
5	0.0515	14.7344
6	0.0801	14.8663
7	0.1158	14.2866
8	0.2003	15.5683
9	0.2487	16.8597
10	0.3069	18.1770
11	0.3345	18.8469
12	0.4305	19.8200
13	0.4797	20.2411
14	0.5741	21.6586
15	0.6335	22.9285

Table 4. Measurement of average speed and friction force - Retraction movement

Experiment no	Average Speed (m/s)	Measured F_f (N)
1	-0.6425	-25.0567
2	-0.5704	-23.3380
3	-0.5101	-21.2896
4	-0.4733	-20.4550
5	-0.4543	-19.8860
6	-0.4485	-18.5383
7	-0.4043	-17.8770
8	-0.3486	-16.1427
9	-0.3063	-15.3400
10	-0.2392	-11.5496
11	-0.2122	-11.3070
12	-0.1551	-8.5537
13	-0.0884	-7.6750
14	-0.0814	-6.5300
15	-0.0326	-4.6699

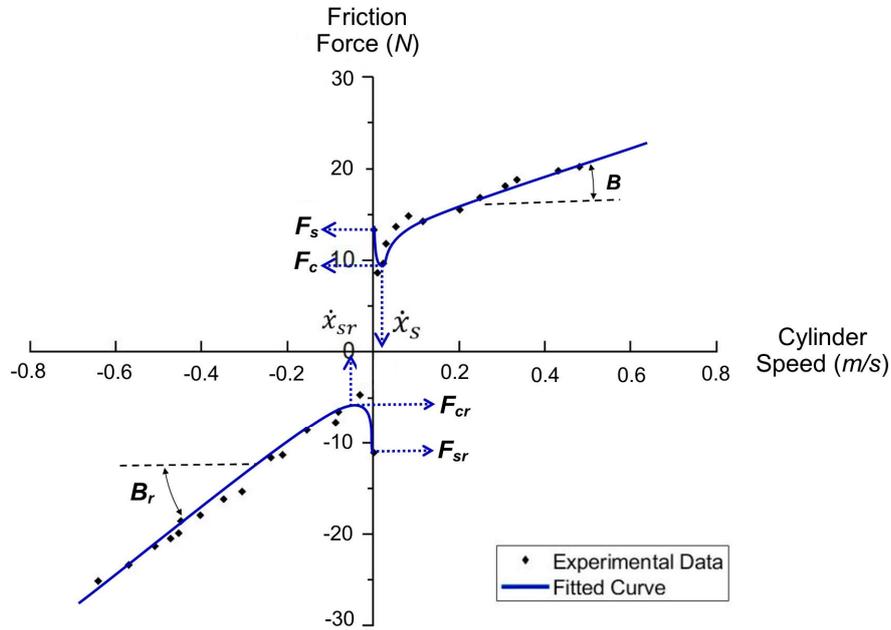


Figure 10. The resultant cylinder speed-friction force graph after experiments and analysis

7. ACKNOWLEDGEMENT

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