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IDENTIFICATION OF FRICTION EFFECTS IN A LINEAR POSITIONING SERVOPNEUMATIC SYSTEM

IDENTIFICAÇÃO DOS EFEITOS DE ATRITO EM UM SISTEMA SERVOPNEUMÁTICO DE POSICIONAMENTO LINEAR

Rodrigo Trentini[1], Alexandre Campos[2], Antonio da Silva Silveira[3], Guilherme Espindola[4]
[1]Leibniz Universität Hannover (LUH), Institut für Regelungs Technik (IRT), Hannover, Germany
E-mail: preuss@irt.uni-hannover.de
Universidade do Estado de Santa Catarina (UDESC), Centro de Ciências Tecnológicas (CCT), Joinville, SC, Brazil
[2]E-mail: alexandre.campos@joinville.udesc.br
[3]E-mail: antonios@joinville.udesc.br
[4]E-mail: espindola.gui@gmail.com

ABSTRACT
It is presented, in this paper, a methodology to identify friction effects in servopneumatic systems using the Karnopp model. In spite of servopneumatic advantages in relation to electric and hydraulic systems, as cleanliness and low cost, its main disadvantages are related to nonlinearities caused by friction effects. Therefore, friction identification plays an important role in servopneumatic research, since the controller design depends on an accurate friction model. In this work, the experimental data are acquired via testbed experiments. The testbed comprises a pneumatic actuator, a potentiometric displacement sensor, two pressure sensors, a manual valve and an acquisition system. The experimental data are used to depict friction in the system using the Karnopp model. Unknown mathematical system coefficients are identified using Least Squares method, where an accuracy percentage of 99.04% between the mathematical and experimental models is reached.
Keywords: Friction identification, Servopneumatic systems, Karnopp model, Least Squares method.

RESUMO
É apresentada, neste trabalho, uma metodologia para a identificação dos efeitos de atrito em sistemas servopneumáticos utilizando o modelo de Karnopp. Apesar das vantagens destes sistemas em relação à sistemas elétricos e hidráulicos, como limpeza e baixo custo, suas principais desvantagens são relacionadas às não-linearidades referente ao atrito. Por este motivo, a identificação do atrito é uma importante área de pesquisa na servopneumática, já que o projeto de controladores para estes sistemas depende diretamente de um modelo de atrito fiel ao sistema real. Neste trabalho, uma bancada de testes é desenvolvida a fim de obter os dados experimentais do sistema. A bancada é composta por um atuador pneumático, um sensor de deslocamento potenciométrico, dois sensores de pressão, uma válvula manual e um sistema de aquisição de dados. Os dados experimentais obtidos são utilizados para representar o atrito do sistema através do modelo de Karnopp. Os coeficientes desconhecidos do modelo matemático são identificados através do método dos Mínimos Quadrados, onde é obtido um percentual de assertividade do modelo matemático de 99,04% em relação aos resultados experimentais.
Palavras-chave: Identificação do atrito, Sistemas servopneumáticos, Modelo de Karnopp, Método dos Mínimos Quadrados.

1 –INTRODUCTION

It is well known that compressed air is one of the oldest forms of energy, but its application in industry took place only since 1950, where it has replaced the human power in repetitive tasks (PERONDI, 2002). Nowadays, compressed air became indispensable in several industrial sections. Pneumatic systems work with high efficiency, performing repetitive operations, saving time, tools and materials. Furthermore, it is a renewable, clean, abundant and cheap energy form. Devices moved by compressed air have a high power/weight relation, low cost, maintenance facility and flexibility in installation. Currently, the main applications in pneumatics are related to linear motion with limits at the end of stroke, among of cutting, drilling, thinning and finishing.

Lately, servopneumatics are being used when intermediate positions are required. These systems use actuators, electronic systems and control valves to reach high-end results. It is important to notice that servopneumatic applications reduce the air consumption by up to 30% in comparison to standard systems (FESTO, 2010).

However, servopneumatic systems present several difficulties in control, as air compressibility and friction effects. Such characteristics make the mathematical model more complex, requiring theinclusion of nonlinear behavior. In pneumatic systems, friction effects occur mainly due to the contact of its internal seals into the actuators casing. These effects are time-varying and also temperature, speed and materials dependent (PERONDI, 2002).

Ali *et al.* (2009) state that friction is the major difficulty to obtain a satisfactory pneumatic model. Friction effects, like Coulomb, static, Stribeck and viscous, cause undesired effects as steady state and tracking errors, stick-slip movements and limit cycles around the desired position (CARNEIRO; ALMEIDA, 2007).

For all the cited reasons, the modeling of friction effects is one of the most important fields of study in servopneumatics, encouraging intense research in the last years.

Nouri *et al*. (2000) deal with the parameter identification problem in servopneumatic system, with special attention to friction effects, using Leuven dynamic model. The friction map is shown, where the parameters before and after the movement are determined.

Using the cited friction model, Andrighetto; Valdiero; Carlotto, (2006) present a friction behavior comparison between eight different kinds of actuators. Coulomb, static, Stribeck and viscous effects are empirically identified for each analyzed actuator.

Dunbar; Callafon; Kosmatka (2001) show an online identification technique using an accelerometer coupled to the servopneumatic system load. Coulomb and viscous effects are identified in simulations.

In Wang *et al*. (2004), a genetic algorithm technique is used to identify the friction effects in a servopneumatic precision system. The presented method provides a friction map with Coulomb, static and viscous effects.

Shirazi and Voda (2003) use the Karnopp model to elaborate a friction map identification method for a pneumatic actuator. The obtained model considers Coulomb and viscous effects, besides a stick-slip region.

Additionally, Carneiro and Almeida (2006) present a friction effects identification methodology for a servopneumatic system using Artificial Neural Networks (ANN). It is cited that dynamic models are able to represent some effects that static ones are not, as hysteresis. However, the use of dynamic models increases the system order. For this reason, a static model that considers the friction hysteresis effects is presented.

In this paper, the model for the friction forces using the Karnopp model is presented in section 2. The friction identification using testbed experiments and Least Squares methods is shown in section 3, whereas theconclusions are presented in section 5.

2 – FRICTION MODEL

Most used static friction models in literature use the follow components: friction forceF_{atr}, mechanical system speed $\dot{x}$, Coulomb force F_c, static friction force F_s, viscous friction B_v and Stribeck speed $\dot{y}_s$, as shown on Figure 1. In Figure 1-a is presented the Coulomb model. In Figure 1-b the static effect is inserted. In 1-c, is considered the viscous friction component, and in 1-d the Stribeck effect is added. It is noted that all the presented maps could be asymmetric, *i.e.*, F_c, F_s, B_v and $\dot{y}_s$ could have different values for positive and negative speeds.

However, neither of the presented models represent a real behavior for null displacement speeds, since the static friction force could assume any value between positive (${F_s}^+$) or negative (${F_s}^-$) values. Carneiro and Almeida (2007) state that, the greater is the model information in low speeds, the higher is the mathematical model accuracy. This is particularly important in pneumatic systems modeling.

Karnopp (1985) has proposed a static friction model which considers the stick-slip effect. In other words, Karnopp model considers the lower possible displacement speed $\dot{x}_{min}$. This model is presented in Figure 2.

Figure 1 – Examples of static friction maps (Carneiro and Almeida, 2007)

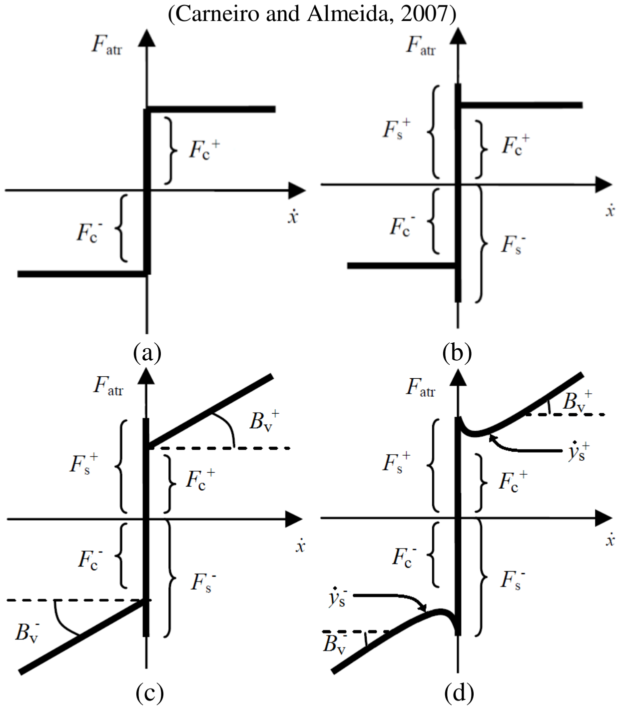
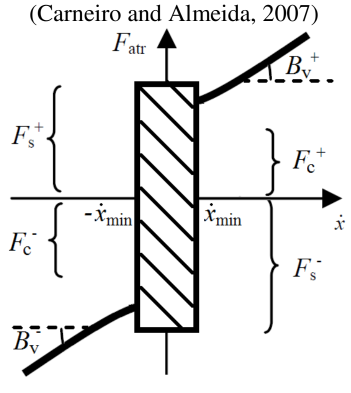


Figure 2 – Karnopp friction force model (Carneiro and Almeida, 2007)



In Figure 2, for $-\dot{x}_{min} < \dot{x} < \dot{x}_{min}$ the system is considered "stuck", while for $\dot{x} \leq -\dot{x}_{min}$ and $\dot{x} \geq \dot{x}_{min}$ the system is considered "slipped" (Carneiro and Almeida, 2007).

Therefore, whether there is enough speed to overcome the stick effect, the Karnopp friction force model, considering Stribeck speed, is given by Equations (1) and (2):

$$F_{atr}^+ = F_c^+ + B_v^+\dot{x} + (F_s^+ - F_c^+)e^{-\left(\frac{\dot{x}}{\dot{y}_s^+}\right)^\delta} \quad (1)$$

$$F_{atr}^- = F_c^- + B_v^-\dot{x} + (F_s^- - F_c^-)e^{-\left(\frac{\dot{x}}{\dot{y}_s^-}\right)^\delta} \quad (2)$$

Where δ is an arbitrary coefficient, usually equal to 2 (Andrighetto; Valdiero; Carlotto, 2006).

Karnopp model, as a static model, does not represent some friction effects. Olsson *et al.* (1998) state that this model is strongly coupled, and the external force is usually an unknown parameter. Carneiro and Almeida (2007) assert that the friction force does not depend only on the speed instantaneously value, but also on the followed trajectory, yielding in hysteresis cycles which Karnopp model cannot represent.

However, even with the cited restrictions, Shirazi and Voda (2003) state that Karnopp model has good compromise between simplicity and the right representation of the main friction effects. For this reason, Karnopp model is the chosen model for the friction effects representation in this work.

3 –FRICTION IDENTIFICATION

Mathematical modeling usually leads to physical system representation. Nevertheless, its internal parameters are not always *a priori* known, and so empirical techniques have to be used in order to allow its analysis and simulations. Thus, it is possible to represent physical systems with little information about its previous behavior.

Mathematical modeling could be divided in three areas related to the system previous information (Aguirre, 2007):

- Phenomenological or white-box modeling, which is the modeling performed through physical system analysis;
- Empiric or black-box modeling, which is the modeling where there are not previous system information, and only empiric data are considered;
- Gray-box modeling, which uses empirical information to complement the system phenomenological model.

Friction phenomenological model on Eq. (1) and (2) containmodel unknown parameters: F_c , F_s , B_v and $\dot{y}_s$. Therefore, this section describes an empirical method to identify these parameter using testbed experiments.

The actuator force equation is given by Newton's 2nd Law, being:

$$F_{atr} = A_{p1}p_1 - A_{p2}p_2 - m_p\ddot{x}_p + m_p g \tag{3}$$

Where A_{p1} and A_{p2} are the piston rod positive and negative displacement cross-sectional area, respectively, p_1 and p_2 are the chamber pressures, m_p is the piston rod mass, x_p is the piston rod displacement and g is the gravitational acceleration.

The previous known parameters are m_p, A_{p1} and A_{p2}. Then, analyzing Equation (3), it can be state that the friction force F_{atr} may be calculated knowing the parameters p_1, p_2 and y_p, which could be measured by pressure and displacement sensors.

3.1 Testbed

The used servopneumatic system is composed by a linear pneumatic actuator, two pressure sensors, a linear potentiometric sensor,manual pneumatic pressure valves, and an acquisition board.

Sensors measure the pressure into the actuator chambers. The linear potentiometric sensor is connected measure displacement. A pressure controls the air supply to one of the chambers, while the other one is kept under atmosphere pressure, depending on which experiment is executed: for positive or negative displacement. It is showed in Figure 3 the cited testbed, and in Table 1 the used materials.

Figure 3 – Bench test (the electronics valve is disabled)

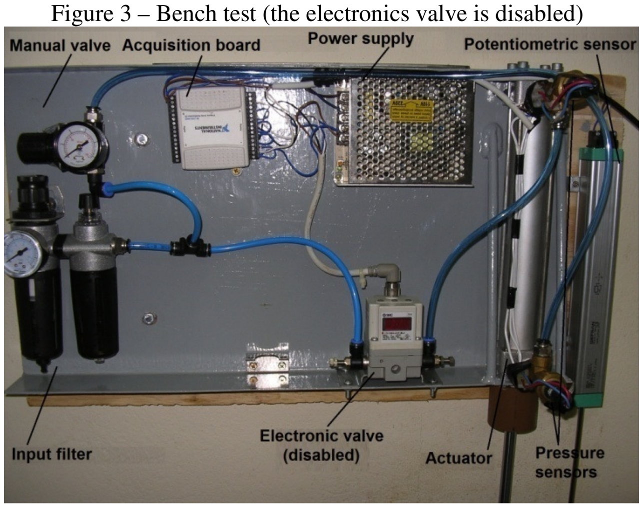


Table 1 – Components employed in the experiments

Material – Brand	Coding
Linear pneumatic actuator – Werk-Schott	CWE-A03273410-0200
Pneumatic pressure valve – Werk-Schott	3102-30
Pressure sensors – Sensata Technologies	100CP2-74
Linear potentiometric sensor – Gefran	LTM-0200S
Data acquisition board – National Instruments	NI USB-6009

The identification has to be performed consideringthe potentiometric sensor friction besides the actuator friction, since the servopneumatic system includes the displacement feedback, which is carried out through the cited sensor measured signal.

The data acquisition is performed through LabView software, using 5 ms for time period, which is the fastest data acquisition time for the implemented application with the cited board. Previous experiments show that the system time constant is around 100 ms.

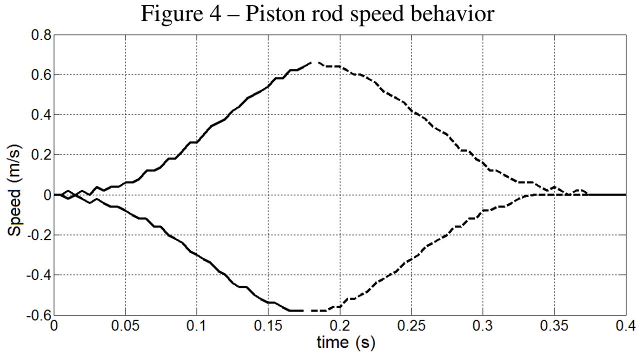
3.2 Experimental results

For carrying out the friction parameters identification, two different tests are performed: for positive and negative displacements. For both, the centralpiston rod position is considered the system initial position. Positive displacements are considered from up to bottom. The step control signal P has amplitude of $3.224 \cdot 10^5$ Pa.

For the positive displacement test, the control signal P is applied into the advancing actuator chamber, while for the negative displacement, it is inserted into the returning actuator chamber.

In Figure 4 is shown the obtained experiments results for positive and negative speeds $\dot{x}_p$, obtained through the piston rod displacement measure.

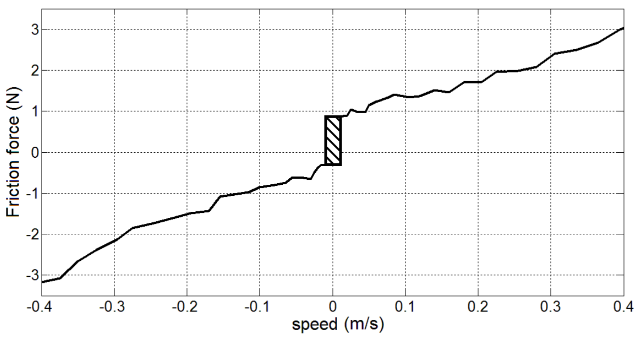
Figure 4 – Piston rod speed behavior



As cited in Section 2, Karnopp model is not able to represent hysteresis cycles. Then, the complementary speed values, represented by the dashed lines, are not considered in this work, since it concerns to hysteresis cycles.

Moreover, in the performed experiments it is stated that the minimum piston rod speed is $\dot{x}_{min} = 0{,}005$ m/s. The obtained system static friction map is shown in Figure 5, using Figure 4 data and Equation 3 data.

Figure 5 – System friction experimental map



In Figure 5 it is noted that the Stribeck effect $\dot{y}_s$ cannot be identified. Stick-slip region is highlighted in hatched area. Hence, rewriting Equations (1) and (2), neglecting this effect, the final equations for parameter identification procedure in this paper are:

$$F_{atr}^{+} = F_c^{+} + B_v^{+}\dot{x} \quad (4)$$

$$F_{atr}^{-} = F_c^{-} + B_v^{-}\dot{x} \quad (5)$$

3.3 Parameter identification

The black-box identification is carried out using Least Squares method. This method consists in minimize the sum of squared residuals, being the residuals the difference between an observed value and the best fit provided by the method. This method is usually used for linear identification (Ljung, 1987).

As are stated with Equations (4) and (5), the nonlinear identification problem is divided into two different linear ones, *i.e.* for positive and negative displacements.

The regression matrix $\dot{\mathrm{X}}$ is given by Equation (6),

$$\dot{\mathrm{X}} = \begin{bmatrix} 1 & \dot{x}(k-1) \\ \vdots & \vdots \\ 1 & \dot{x}(N-1) \end{bmatrix} \quad (6)$$

Where $\dot{x}$ is the measured speed, $k = 1, 2, \ldots, N$, and N is the total observations number.

The parameters vector $\widehat{\Theta}$ is obtained through Equation (7),

$$\widehat{\Theta} = \begin{bmatrix} F_c \\ B_v \end{bmatrix} \quad (7)$$

And it is determined solving the linear system given in Equation (8),

$$\widehat{\Theta} = [\Psi^{\mathrm{T}}\Psi]^{-1}\Psi^{\mathrm{T}}\mathrm{Y} \quad (8)$$

Where Y is given by Equation (9),

$$\mathrm{Y} = \begin{bmatrix} F_{atr}(k) \\ \vdots \\ F_{atr}(N) \end{bmatrix}. \quad (9)$$

Using the speed and friction force values presented in Figure 5 to solve Equation (9), the identified friction parameters of Equations (4) and (5) are shown in Table 2.

Table 2 – Identified friction parameters

Parameter	Value [Unit]
F_c^{+}	0.74 [N]
F_c^{-}	-0.26 [N]
B_v^{+}	5.4 [Ns/m]
B_v^{-}	6.7 [Ns/m]

On Figure 6 is shown the experimental results using the identified values presented in Table 2.

In order to measure the identified model accuracy, it used the Coefficient of Multiple Correlation R^2, given according to Equation (10),

$$R^2 = 1 - \frac{\sum_{k=1}^{N}[y(k) - \hat{y}(k)]^2}{\sum_{k=1}^{N}[y(k) - \bar{y}]^2} \quad (10)$$

Where$y(k)$ is the measured data, $\hat{y}(k)$ is the identified data, $\bar{y}$ is $y(k)$ arithmetical average.

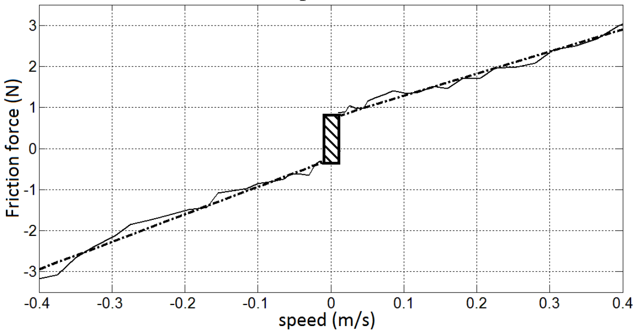
Using Equation (10), the mathematical model accuracy percentage reaches 99.04% of the measured data.

CONCLUSIONS

This paper identifies friction effects for a linear positioning servopneumatic system.

Using bench test experiments, it is possible to verify the experimental static friction map. The system consists in a pneumatic actuator, a potentiometric displacement sensor, two pressure sensors, a pressure valve and an acquisition board.

Figure 6 – Measured (—) and identified (- · -) system friction responses



For friction identification purpose, it is used the Karnopp model. It is noted that static and Stribeck effects could not be identified due to the stick-slip region, so that these effects are neglected in the final model.

For Coulomb and viscous effects identification, the Least Squares method is used. The empirical model accuracy reaches 99.04% regarding to the experimental measured data.

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REFERENCES

AGUIRRE, L. A. **Introdução à identificação de sistemas: Técnicas lineares e não-lineares aplicadas a sistemas reais**. Editora UFMG, 2007.

ALI, H. I.; BAHARI, S.; NOOR, B. M.; BASHI, S. M.; MARHABAN, M. H. A review of pneumatic actuators (Modeling and Control). **Australian Journal of Basic and Applied Sciences**, v. 3, n. 2, p. 440-454, 2009.

ANDRIGHETTO, P. L.; VALDIERO, A. C.; CARLOTTO, L. Study of the friction behavior in industrial pneumatic actuators. **ABCM Symposium Series in Mechatronics**, p. 369-376, 2006.

CARNEIRO, J. F.; ALMEIDA, F. G. Modeling pneumatic servovalves using neural networks. **IEEE Internatinal Conference on Control Applications**. Munique, p. 790-795, 2006. https://doi.org/10.1109/cacsd.2006.285478 https://doi.org/10.1109/cacsd-cca-isic.2006.4776746.

CARNEIRO, J. F.; ALMEIDA, F. G. Comparação entre dois modelos do atrito num sistema servopneumático. ***In***: 8th Congresso Iberoamericano de Engenharia Mecânica. Cuzco, 2007.

DUNBAR, W. B.; CALLAFON, R. A.; KOSMATKA, J. B. Coulomb and viscous friction fault detection with application to a pneumatic actuator. **Proceedings** of IEEE/ASME International Conference on Advanced Intelligent Mechatronics. Como, Italy, 2001. https://doi.org/10.1109/aim.2001.936889.

FESTO. **Servopneumatics**. *Brochure*, Apr. 2010.

KARNOPP, D. Computer simulation of slip-stick friction in mechanical dynamic systems. **Journal of Dynamic Systems, Measurement and Control**, v. 107, n. 1, p. 100-103, 1985. https://doi.org/10.1115/1.3140698.

LJUNG, L. **System identification: theory for the user**. Prentice-Hall, 1987.

NOURI, B. M. Y.; AL-BENDER, F.; SWEVERS, J.; VANHERCK, P.; BRUSSEL, H. Modelling a pneumatic servo positioning system with friction. **Proceedings** of the American Control Conference, p. 1067-1071, 2000. https://doi.org/10.1109/acc.2000.876664.

OLSSON, H.; ASTROM, K. J.; WIT, C. C. de; GAFVERT, M.; LISCHINSKY, P. Friction models and friction compensation. **European Journal of Control**, v. 4, n. 3, p. 176-195, 1998. https://doi.org/10.1016/S0947-3580(98)70113-X.

PERONDI, E. **Controle não-linear em cascata de um servoposicionador pneumático com compensação do atrito**. Tese (Doutorado), Universidade Federal de Santa Catarina – UFSC, 2002.

SHIRAZI, L. R.; VODA, A. B. Friction identification using the karnopp model, applied to an electropneumatic actuator. **Proceedings** of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, v. 217, p. 123-138, 2003. https://doi.org/10.1177/095965180321700206.

WANG, J.; WANG, J. D.; DAW, N.; WU, Q. H. Identification of pneumatic cylinder friction parameters using genetic algorithms. **IEEE/ASME Transactions on Mechatronics**, v. 9, p. 100-107, 2004. https://doi.org/10.1109/TMECH.2004.823883.