DEVELOPMENT OF A DIDATIC EQUIPMENT FOR PNEUMATIC COMPONENT SIZING

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Abstract. This paper presents the design of a didactic equipment for engineering teaching in the pneumatic field. A brief analysis of the main pneumatic components required in the experimental teaching are showed, resulting in the construction of a system that enables the design and the integration of electronics with pneumatics and programming. With a modular construction used this system allows the experimental teaching in the context of mechanical and mechatronic engineering. Therefore, the concepts of compressible flow throughout valves, conservation of mass in cylinder chambers and Newton's second law to the piston are applied to the design of pneumatic circuits under distinct loading condition and for different pneumatic components. The equipment conception aims to allow to the students to understand the valve parameters choice according to ISO 6358. The dynamic behavior of the air in the cylinder chambers and tubes can be observed considering several requirements, such as: the necessity to accelerate different masses, to move the piston against adjusted friction forces and/or load forces, and to displace and to hold weights in the vertical position. The design results in the equipment where students will have the opportunity to assembly pneumatic circuits under the automation point of view. However, the choice of the optimum size of valves and pneumatic actuators is the focus of the project where equations for the pneumatic systems sizing and a dynamic model based on software Matlab-Simulink are used. Thus, it will be possible to study several aspects related to pneumatic systems, such as: Speed control (extending and retracting) under variable load conditions, weight holding in the vertical position, cylinder synchronizing, stroke-end cushioning adjustment, acceleration /deceleration of pistons and motors, and vacuum technology.

Keywords: Pneumatic Components Sizing, Didactic Equipment, Design Methodology

1. INTRODUCTION

The pneumatic component selection has as search source the catalogs of manufacturers and, for an efficient use of these data it is important the knowledge of both theoretical principles and rules that established the test conditions of these components. In this context, the objective of this paper is to present information on the development of a didactic System for Pneumatic Circuits Sizing *SPCS*, destined to aid the graduation courses in mechanical engineering and industrial automation and control engineering, as well as the post-graduate courses in mechanical engineering, establishing the relationship between the pneumatic systems, electronics and the programming.

The industrial necessity to offer consumer products that offer better precision and guarantee has justified the use in larger scale of pneumatic systems in its production lines. The pneumatic replaces, with great benefits, the obsolete instruments moved by conventional mechanical actuators. Combining the operation of pneumatic systems to modern computing resources, it is possible to increase the productive capacity of industries, enabling the execution of tasks faster and more securely.

Hence post-graduate and undergraduate students need to assimilate, both in practical and theoretical ways, the basic concepts of operation of pneumatic equipments to be able to exercise of their post-academic professional activities.

The didactic equipment for the teaching of pneumatic available in the market is mainly designed for pneumatic circuits' assembly and/or to the integration of pneumatic with control systems and PLC's. Otherwise, the equipment presented in this paper has as main objective to support the teaching of pneumatic components' sizing, providing experimental verification for the theoretical concepts previously assimilated by the students.

Regarding the structure of the paper, section 2.0 describes the didactic system for pneumatic components sizing; in section 3.0 is presented the sizing of the system and the mathematical modeling, in section 4.0 the results of the simulations are shown, and in section 5.0 the conclusions.

2. DIDACTIC EQUIPMENT

The didactic equipment SPCS has the innovative objective to include practical aspects of pneumatic system's sizing. A feature that is not offered by other didactic equipment available in the market is the possibility to mach valves and actuators under different both loadings and positions aiming to observe the sizing limit conditions. However, the

SPCS has other important feature, since a multidisciplinary character was adopted as a concept that is the complementary focus in process automation and Programmable Logic Controller (PLC) programming.

The equipment is composed of four workstations, as shown in Fig. 1, and is designed to accommodate 4 groups of students working either independently or simultaneously. Each workstation has pneumatic actuators for different applications (see Fig. 2). For a flexible operation, the workstation user can perform the tests manually and in a more advanced stage of study, the tests can be automated. In this equipment's automated operation mode the workstations can operate in an integrated mode with each other, thus allowing the implementation of a continuous cycle between them. The main didactic objective of this equipment is to make the student deal with mathematical modeling and with the consequences that a bad sizing can cause. Therefore, exercises that impose conditions that require accurate sizing are proposed to the students.
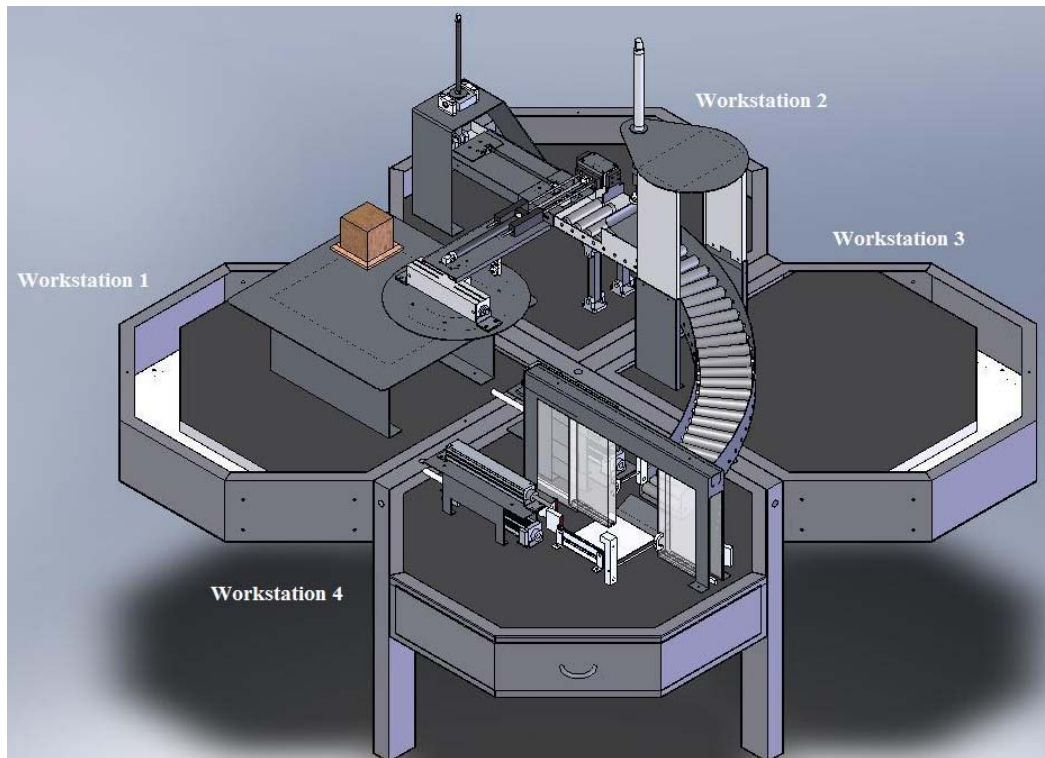

Figure 1. Didactic equipment SPCS

According to the pneumatic diagrams in Fig. 3, the workstation 1 includes the use of a semi-rotary drive (1A2), a gripper type actuator (1A1) and a linear guide cylinder (1A3). The workstation 2 includes the use of two linear cylinders (2A1 and 2A2). However, these actuators are used in three different positions: vertical, horizontal and inclined. The workstation 3 includes the use of a vacuum generator (3A2) and a linear cylinder (3A1). The system implemented on the workstation 4 includes the use of two linear pneumatic actuators (cylinders) (4A1 and 4A2), opposed to other two hydraulic cylinders (4Z1 and 4Z2), where the hydraulic cylinders act as a load for the pneumatic ones. Thus, a situation is didactically simulated where the pneumatic cylinder moves a high load. All workstations were designed to work as standalone workstations or integrated to the others.

3. ESTATIC AND DINAMIC SIZING

The selection and sizing of the components are essential activities on the design of pneumatic systems. The correct selection of components is of vital importance and it consists of choosing, in a coherent way, the characteristics of the components in agreement with the initial requirements imposed to the design.

When an incorrect sizing is made, the characteristics of the solution are reflected in the quality of the design, resulting in a system that does not meet the initial needs and in either undersized or oversized components.
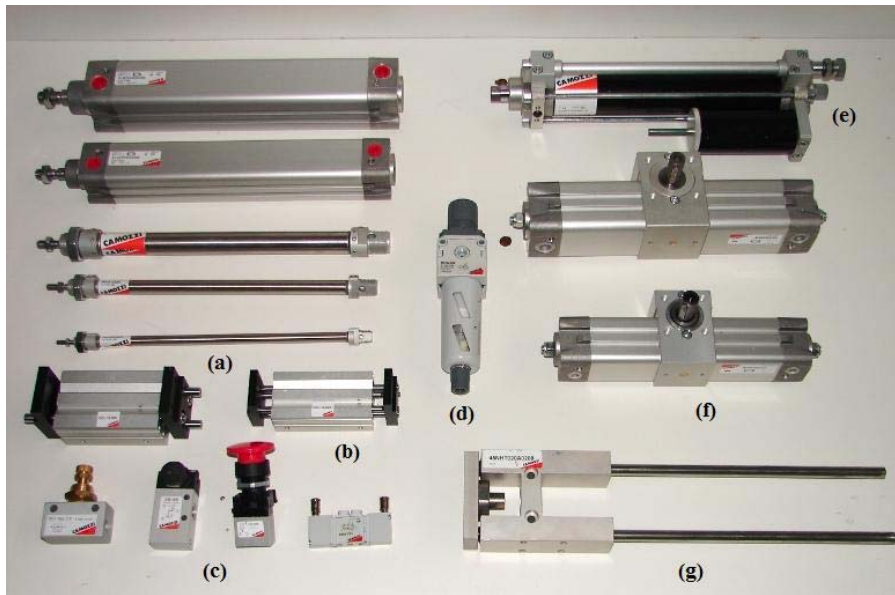
Figure 2. Actuators that compose the equipment: (a) linear actuators, (b) gripper actuators, (c) valves, (d) air filter, (e) hydraulic cylinders, (f) semi-rotary drives, (g) linear guide (Camozzi, 2006)
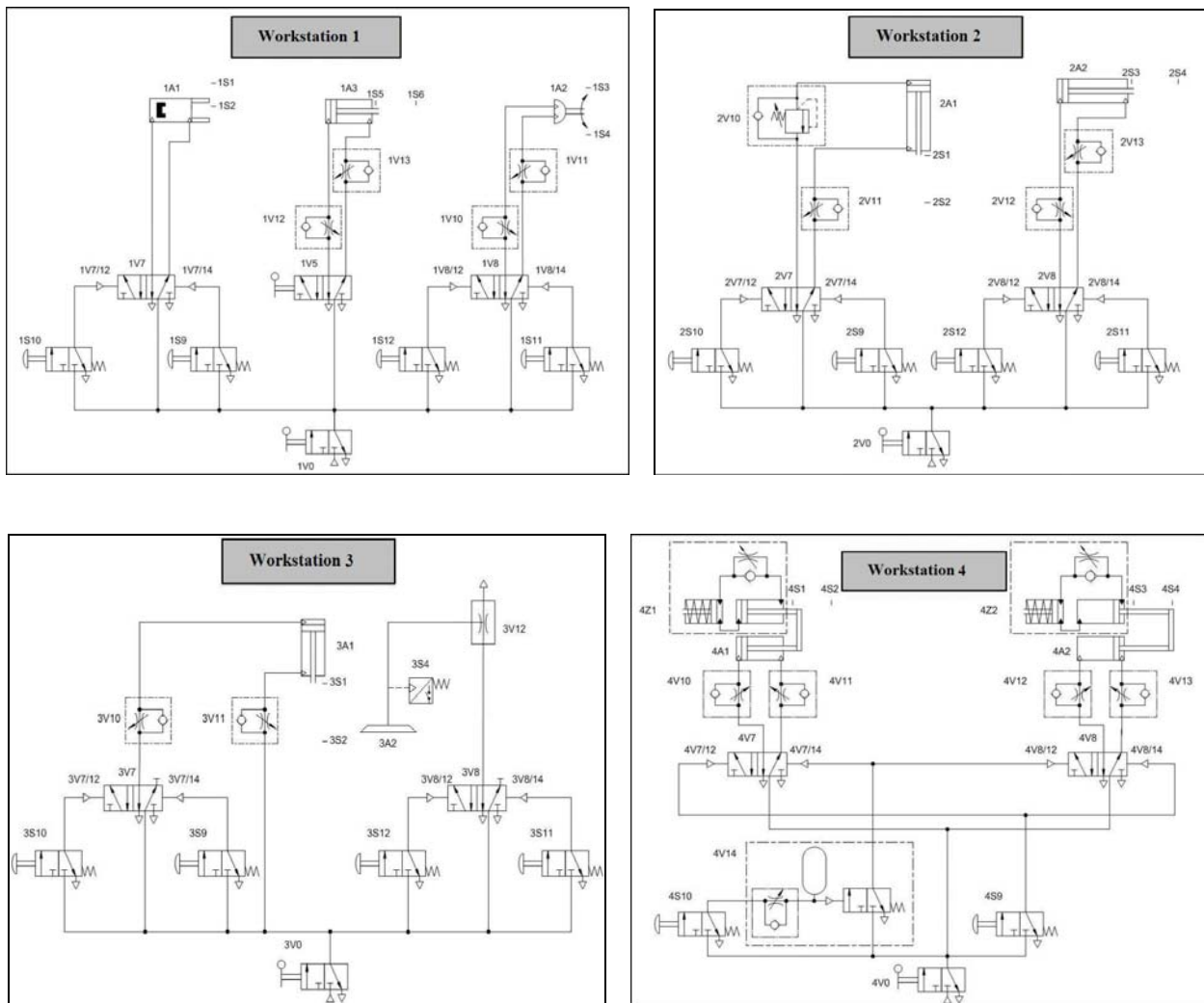

Figure 3. Pneumatic circuits of the workstations

In undersized systems, components with a lower capacity than the requested are chosen. This can cause serious problems of lack of power to perform the required tasks. As a result, the system is usually sized with a safety factor, that in some cases increase the design values up to 50% that results on an oversized system. In general, the bigger the size of the pneumatic component, the more expensive it is and the greater is its air consumption, and therefore, it adds unnecessary costs to the design.

A simplified approach to the process of valves and cylinders sizing is shown in this section and detailed in Asaff (2006). In Fig. 4, the basic pneumatic circuit is shown displaying the variables involved in the sizing.
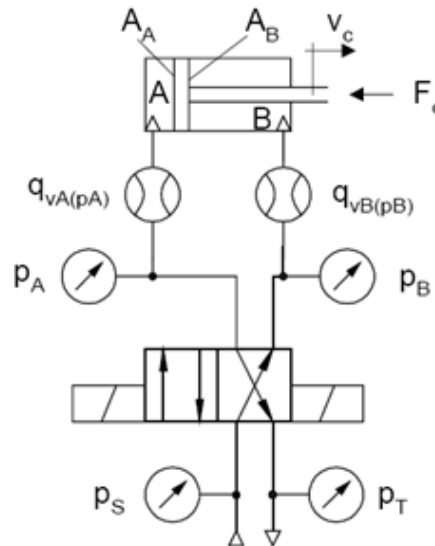

Figure 4. Basic pneumatic circuit

Where,

- F_c is the load force;
- v_c is a velocity of the piston;
- p_A and p_B are the absolute pressure, in the cylinder chambers;
- A_A and A_B are the piston areas of the cylinder;
- $q_{VA}(p_A)$ is the air volumetric flow rate, measured at the pressure p_A;
- $q_{VB}(p_B)$ is the air volumetric flow rate, measured at the pressure p_B;
- p_S is the absolute supply pressure;
- p_T is the absolute exhaust pressure

A dynamic model of a pneumatic system developed in Asaff (2007) was adapted to the specific case of this research to aid the choice of the valves and actuators sets that would meet the requirements of the exercises and to verify aspects of the dynamic sizing.

As presented in Scholz (1990), the mass flow rate through the valve is modeled according to the ISO 6358 standard (ISO, 1989), which describes the state of the subsonic flow through an elliptic curve which is dependent on the parameters b (critical pressure ratio) and C (sonic conductance).

Therefore, the mass flow rate is described by Eqs. (1) and (2), which are valid for the subsonic ($a > b$) and sonic ($a \leq b$) conditions, the latter including the saturated flow that occurs when the pressure ratio is lower than the critical pressure ratio. The coefficients representing the mass flow capacity of the pneumatic component (C and b) are defined according to ISO 6358 (ISO, 1989).

The coefficient b is the pressure ratio below which flow becomes choked, and the coefficient C is the mass flow rate through the component divided by the product of the upstream pressure and the mass density at standard conditions[1] when the flow is choked. (ISO, 1989).

The mass flow rate through the valve is described by Eq. 1.

$$q_m = C p_1 \rho_o \sqrt{\frac{T_o}{T_1}} w(a) \tag{1}$$

For flow rates where the pressure ratio is higher, lower or equal to the critical pressure ratio, the function *w(a)* is given by Eq. (2).

$$
w(a) \begin{cases} = \sqrt{1 - \dfrac{(a-b)^2}{(1-b)^2}} & \text{for} \quad a > b \\[4mm] = 1 & \text{for} \quad a \leq b \end{cases}
\tag{2}
$$

Where, a= (p_2/p_1) and b= $(p_2/p_1)_{cr}$, p_1 and p_2 are the absolute pressures at the upstream and downstream of the orifice, respectively. T_1 is the upstream temperature, T_0 is the temperature at the NTP[1], ρ_o is the density at NTP and C is the sonic conductance.

The coefficient C, defined in ISO 6358 (ISO, 1989), can be correlated with the nominal flow rate (Qn) defined by VDI 3290 (VDI, 19--). As presented in Asaff (2006) and Vieira (1998), the equivalent coefficient C, relative to VDI 3290, can be calculated by Eq. 3.

$$
C_{(VDI3290)} = \frac{Q_n}{p_{1n} w(a_n)}
\tag{3}
$$

For the cylinders the dynamic behavior of the air in the chambers is described through the conservation of mass or energy laws. The hypothesis of isentropic flow and no internal or external leakage of the chambers are considered.

The equation of continuity implemented for the cylinder chamber is given by the following expression:

$$
\frac{dp_A}{dt} = \frac{\gamma}{A_A x + V_{A0}} (R T_A q_{mA} - A_A \dot{x} p_A)
\tag{4}
$$

where "q_{mA}" is the mass flow rate from the valve to chamber A, "V_{A0}" is the dead volume in chamber A including the pipelines; "T_A" is the absolute temperature in chamber A, "R" is the gas constant equivalent to 287 J/kg.K, "A_A" is the piston area, x is the displacement of the cylinder; "γ" is the specific heat ratio at constant pressure and constant volume.

Likewise, the continuity equation for the B chamber of the cylinder can be written in the following form:

$$
\frac{dp_B}{dt} = -\frac{\gamma}{A_B (L - x) + V_{B0}} (R T_B q_{mB} - A_B \dot{x} p_B)
\tag{5}
$$

where: "q_{mB}" is the mass flow rate from the valve to chamber B, "L" is the cylinder stroke and "V_{B0}" is the dead volume in chamber B including the pipelines; "T_B" is the absolute temperature in B chamber, "A_B" is the annular area and "γ" is the specific heat ratio at constant pressure and constant volume.

For a system in steady state conditions, the volumetric flow in the chamber of the cylinder can be described by Eq. (6), which is used for the preliminary selection of the valve.

$$
q_{vA(pA)} = A_A v_A
\tag{6}
$$

The linear motion of the piston is dictated by the application of Newton's Second Law which establishes that the sum of forces acting at any instant must be equal to the product of mass by acceleration ($M_t.a$). Thus, for an asymmetric double-acting cylinder as shown in Figure 4, the movement equation is:

$$
(A_A \cdot p_A)) - (A_B \cdot p_B) = M_t \cdot \frac{d^2 x}{dt^2} + F_{fr} + F_e
\tag{7}
$$

---

[1] NTP: Normal Temperature and Pressure: p=1.013x10^5Pa (1.013bar), T=20°C (293.15K), ρ=1.204 kg/m^3.

Where $(p_A.A_A)$ is the force applied in A_A due to the pressure p_A, $(p_B.A_B)$ the force applied in A_B due to pressure p_B. The variable F_{ft} is the force resulting from friction in the cylinder and the external load and F_e is the effective force available to the rod for movement of load. The total mass M_t is the total mass of the load piston.

The mechanical efficiency n_m of a cylinder is the ratio between the theoretical force or pneumatic force (F_p) and the effective (real) force available for the load movement. For the sizing of a pneumatic actuator, the efficiency is a magnitude that characterizes the steady state system, with constant velocity and zero acceleration, so that, according to Eq. (8), the effective force is equal to the pneumatic force reduced the friction force. Thus, the mechanical efficiency is expressed as:

$$\eta_m = \frac{F_e}{F_p} = \frac{F_e}{(A_A \cdot p_A) - (A_B \cdot p_B)} \tag{8}$$

A value range between 0.80 and 0.90 of n_m (cylinder efficiency) is shown in literature and catalogs of manufacturers. This value range is consistent with the average friction force F_{ft} presented on commercial pneumatic cylinders. According Asaff (2007), Machado (2003) and Andrighetto (2005) these values of F_{ft} are between 10 and 15% of the nominal cylinder force, as shown in regions 1 and 2 (Fig. 5). The knowledge of the required force allow to calculate A_A and the appropriate value of cylinder diameter.
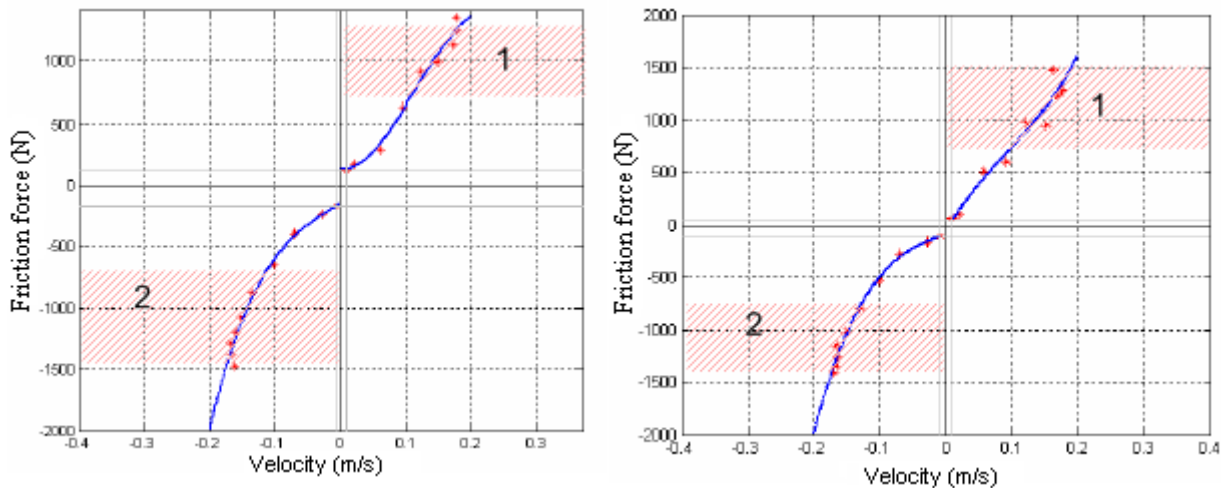

Figure 5. Friction-velocity maps of two different cylinders with F_n=7360N, $F_{ft\ media}\approx$ 736N to 1104N (10 a 15% of F_n) (adapted of Asaff, 2007)

3.1. Dynamic modeling

The implementation of the model was performed by MATLAB / Simulink, in which the representation of the mathematical model is performed through block diagrams, as shown in Fig. 6. The simulations made with this dynamic model were compared with the response of the system using the steady state equations (Eq. 6 and 8).
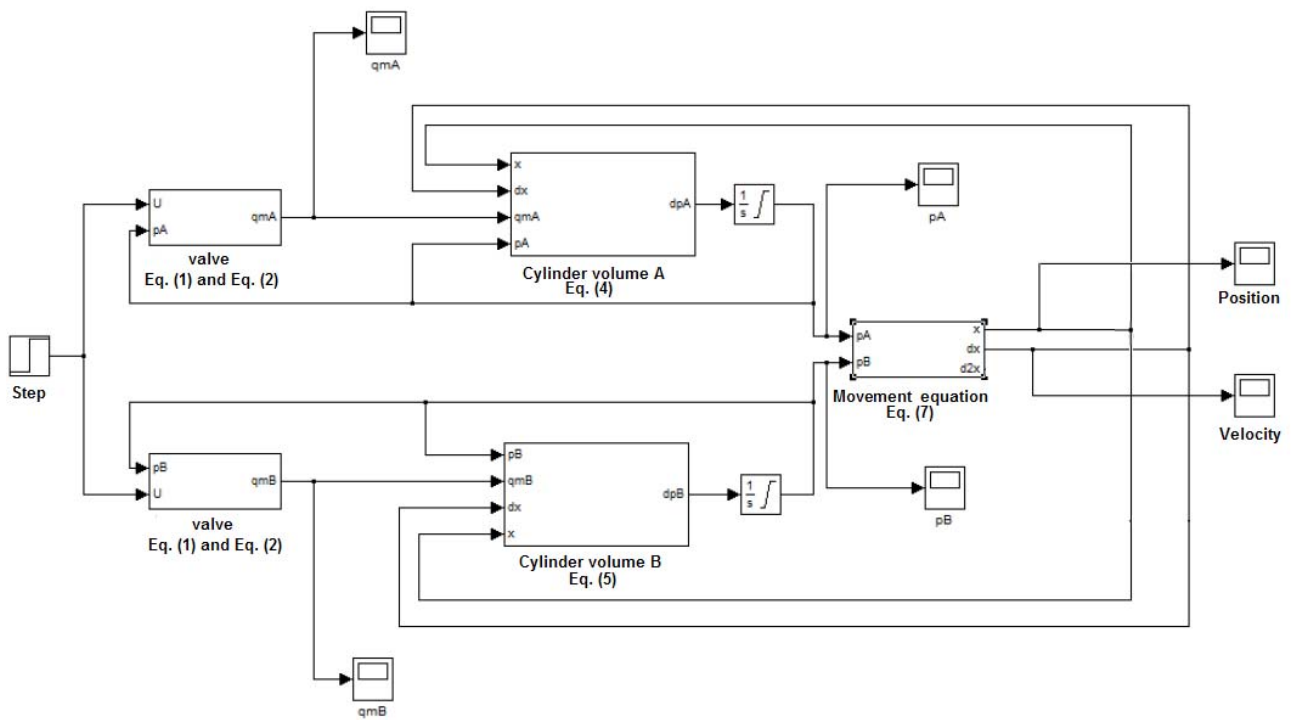
Figure 6. Representation of the mathematical model of the system in block diagrams.

4. RESULTS

The didactic equipment shown in Fig. 7 was constructed at the Laboratory of Hydraulic and Pneumatic Systems (LASHIP), Department of Mechanical Engineering, Federal University of Santa Catarina.
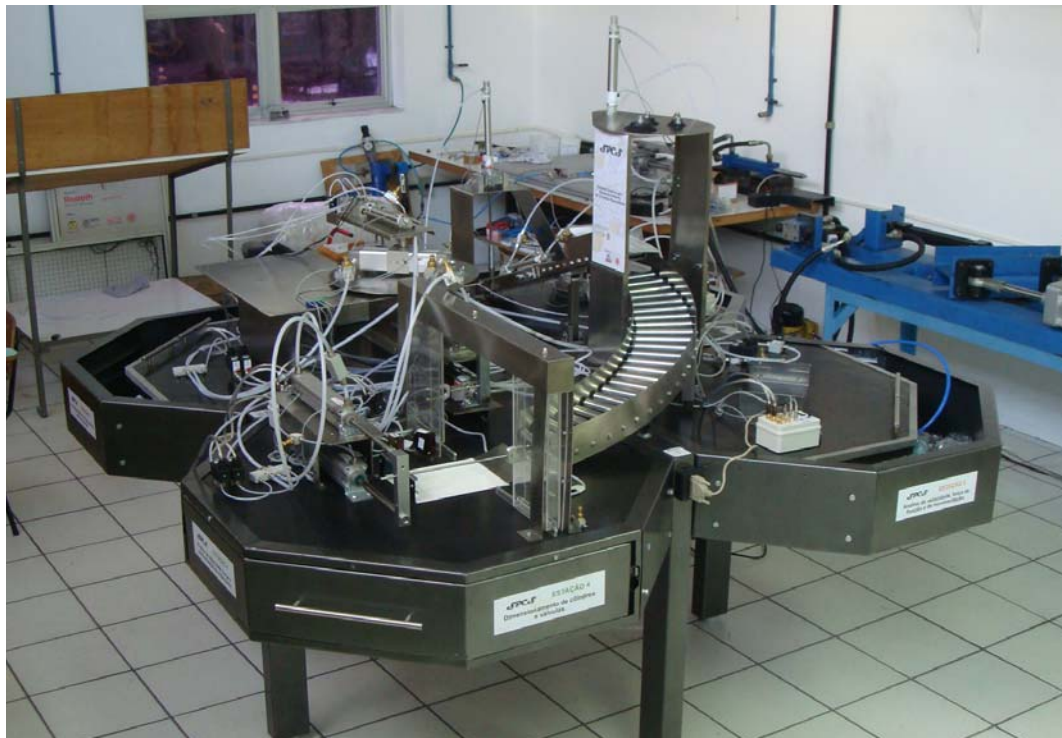

Figure 7. Systems for Pneumatic Circuit Sizing (SPCS)

Using the Simulink model, simulations were made for each acting circuit of each workstation. Loading different conditions with different cylinder-valve match were adopted to observe and analyze the behavior of the system including the settling time and the maximum velocity achieved by the cylinders. The figures below show the position evolving during the movement of the cylinder.

One of the simulated cases (Fig. 8) was the mass variation of the system's load that consisted of several didactic cubes with different masses. For the control of the cylinder (diameter 8mm) a valve with C = 15.10e-9L/bar.s was used. The supply pressure value used in all cases was 6 bar effective.

In this simulation situation, the only external force against to the movement is the friction force of the load mass (cube) with the rollers of the equipment. However, as the friction coefficient of the rollers is very low, the friction force has a low influence on the movement (Boaventura, 2008).

One observes in Fig. 8 the performance of the system using the cylinder of 8 mm diameter, the smallest available cylinder on the system. It has force enough to move the load mass with the heaviest weight. Using the lighter loads, the system advances faster, resulting in a smaller settling time.

In another case, the system is operated with a cylinder of 16mm diameter in the vertical position, with a variation of external force against the motion given by the weight of the cube. Thus, the force is significant and imposes limits to the size of the cylinder. Fig. 9 shows that an undersized cylinder is not able to lift the 8 kg load and this cylinder did not move.
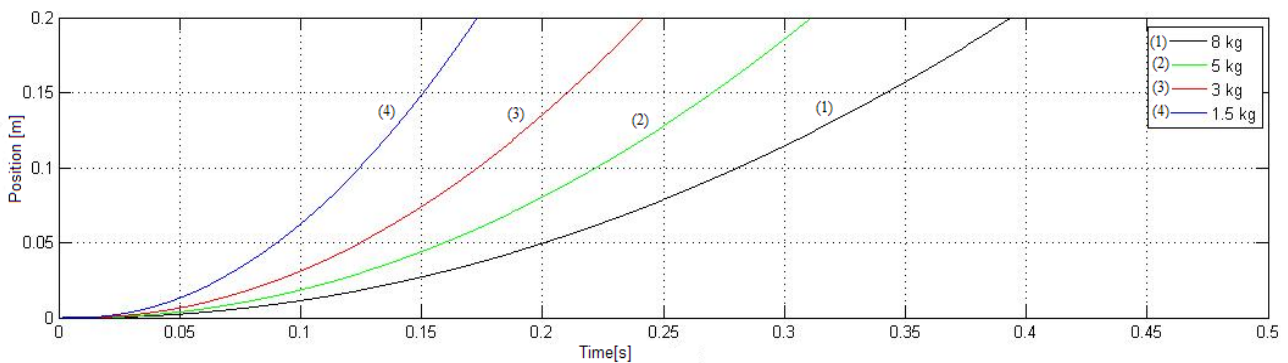

Figure 8. Simulation of the system with mass variation for a cylinder of 8 mm in horizontal position.
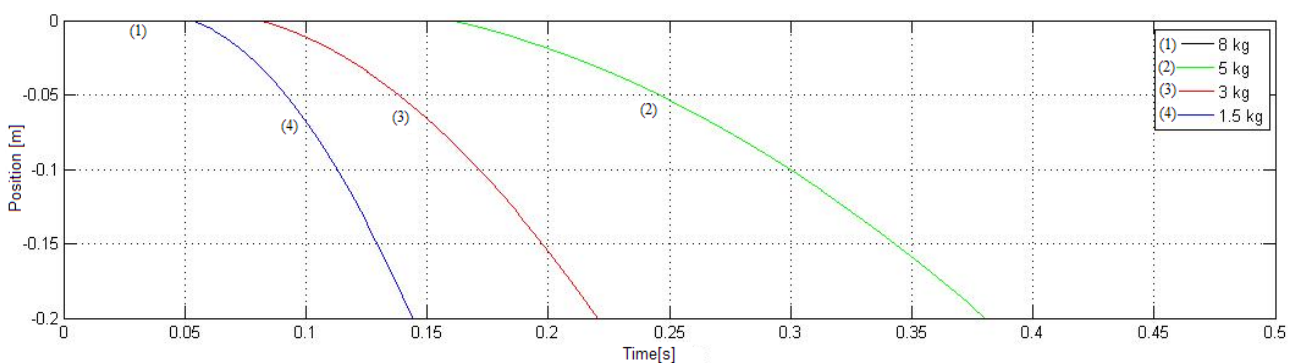

Figure 9. Simulation of the system with mass variation for a cylinder of 16 mm in the vertical position.

Changing the valve and keeping the same load mass, one can analyze the effects of the use of valves with different flow rates. In the case shown in Fig. 10, where the cylinder of 8 mm is used, one can observe that the higher the nominal flow rate of the valve, the faster the cylinder will reach the end of the stroke.
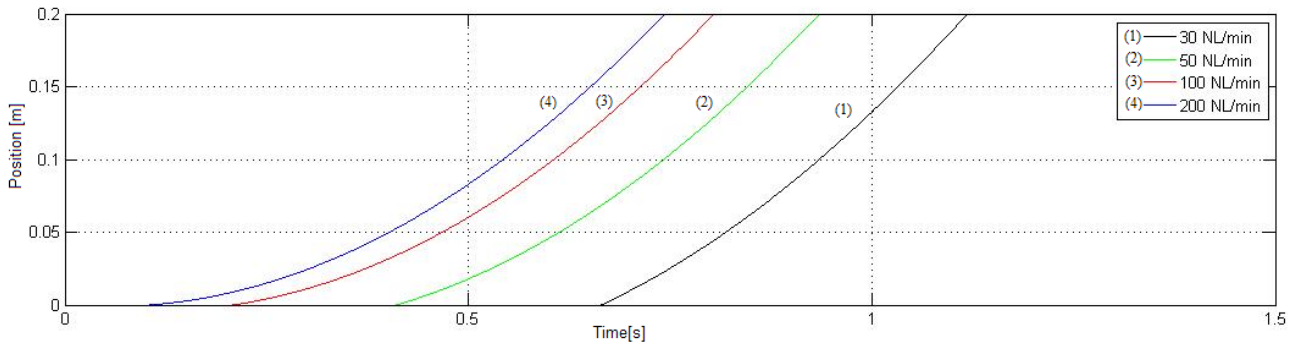
Figure 10. Simulation for different sizes of valves for a cylinder of 8 mm in inclined position

In Fig. 11 the settling times for workstation 4 with different valve sizes are shown but with the external force increased caused by the adjustment of the viscous friction on the hydraulic cylinder coupled the pneumatic one. This load force increasing causes higher cylinder settling times. The dashed curves (in straight line) show that the cylinder achieves the end stroke in lower times due to the use of steady-state equations that disregard transient effects (Eq. 6 and Eq. 8).
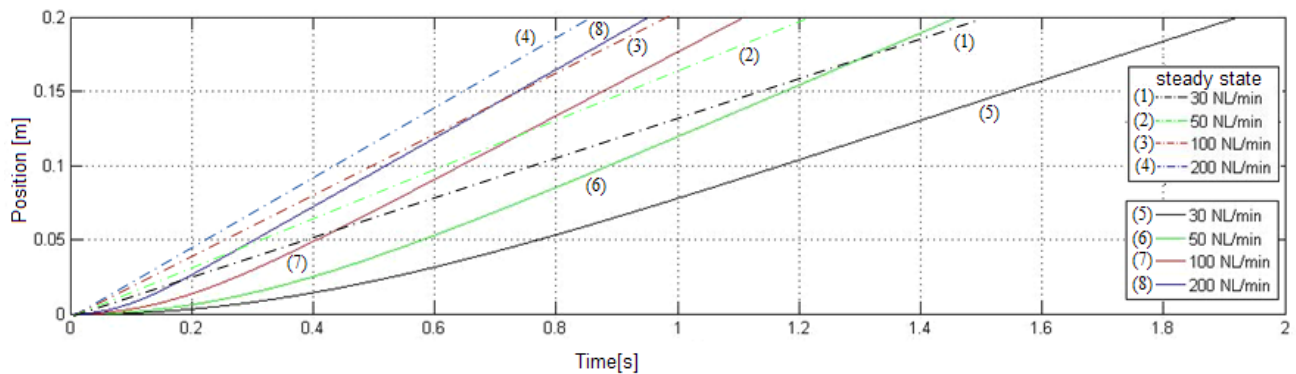

Figure 11. Simulation with a cylinder of 32 mm with the viscous friction coefficient B = 1500 and different valves.

These and others dynamic simulations created guidelines to the choice of both the pneumatic components that should be available to the equipment users (students) and the load masses of the didactic cubes.

5. CONCLUSIONS

This paper presented the conception of a modular didactic equipment designed and constructed for the sizing of pneumatic components with the objective of being a tool that allows theoretical and experimental teaching on engineering. Furthermore it allows the integrated use of pneumatic and mechanical components with electronic systems and programming techniques.

The models that are necessary for the sizing and study of the behavior of pneumatic components (cylinder and valves) were presented, taking into account the use of concepts as compressibility of fluid, conservation of mass and classic mechanical to obtain the dynamic and steady state model. The characteristics of the different configurations of acting systems (cylinder and valve) of specific workstations that compose the didactic equipment were analyzed.

Theoretical aspects of the cylinder and valve sizing complying with the ISO 6358 standard and practical aspects such as velocity control under different load conditions, different positions of the pneumatic cylinders and applications of vacuum technology were studied.

6. ACKNOWLEDGEMENTS

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