An approach to multibody simulation of pneumo-mechanical systems

Paolo Righettini, Alessandro Tasora, Hermes Giberti
Polytechnic of Milan
Department of Electrical Engineering
P.zza L. da Vinci 32, Italy, 20133 Milano
paolo.righettini@polimi.it, tasora@mech.polimi.it, giberti@mech.polimi.it

Abstract: This work describes a method for the simulation of multiple pneumatic actuators in a context of multi body mechanical systems. The model of the single actuator is based on elliptical approximation of non-linear pneumatic devices; friction and sticking phenomena are considered as well. Pneumatic devices introduce forces and new state variables into the complete multibody system: we developed a scheme which minimizes the computational effort for the integration process. After many comparisons with data coming from an experimental device, results provided by our simulation engine proved to be reliable and easy to use. Finally, as an example of a complex multibody device with pneumatic actuators, we present the model of a 3DOF parallel robot whose motion is achieved by means of three pneumatic cylinders, each controlled by a 5-3 proportional valve.

KEYWORDS: MULTIBODY, PNEUMATIC ACTUATORS

1 INTRODUCTION

Pneumatic technology plays a significant role in designing low-cost automatic devices exploiting good compromise between size and payload, high power/weight ratio and easy achievement of linear motion.

The development of pneumatic systems can be noticeably improved by the knowledge of the effects caused by air compression, so that optimal control schemes can be elaborated in order to get the best dynamical performance.

In this paper we discuss how the equations which describe the behaviour of generic pneumatic actuators can be integrated in our software for general-purpose multibody simulation.

The pneumatic model which we adopted for the description of a single actuator is based on elliptical approximation of non linear behaviour of pneumatic devices. Friction and sticking phenomena are considered too.

We introduce multiple pneumatic actuators in a single multibody model, by coupling cylinders with complex mechanisms such as, for example, parallel robots. Hence the simulation of a complex pneumatic-mechanical system may require a huge computational effort, either because of the large amount of variables, either because of the small time

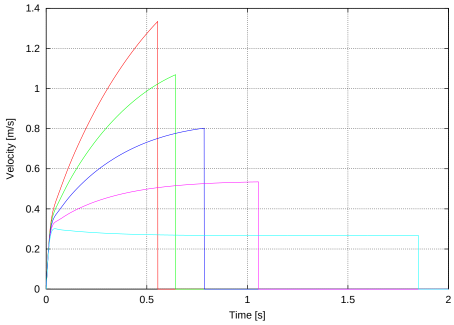

Fig.1: *Simulation tests*

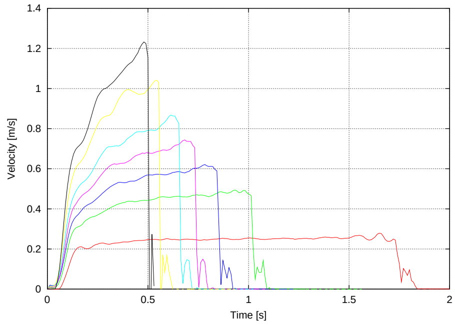

Fig.2: *Experimental tests*

step needed for the integration. For this reason, ad-hoc numerical optimizations have been taken into account.

The resulting multibody code has been validated through experiments performed on a test bed which has been built for this purpose, also introducing the feedback of a closed-loop position control. These tests show a good agreement between computed results and experimental results, therefore our numerical method can be efficiently used to study the behaviour of complex automatic systems with multiple controlled pneumatic devices.

As a final result, the simulation of a 3-DOF pneumatic parallel robot has been performed, and the agreement with the experimental tests has been verified.

2 MATHEMATICAL MODEL

The mathematical model of the pneumatic actuator's dynamic and of the air flow through the inlet and outlet valves, is based on well known equations, like presented in [3]. The matrix form of the the mathematical model of the actuator is shown in the following equation

$$\mathbf{x} = \mathbf{A}\dot{\mathbf{x}} + \mathbf{c} \tag{1}$$

$$\mathbf{x} = [x, \dot{x}, P_a, P_b]^T$$

$$\mathbf{x} = \left[\dot{x}, \ddot{x}, \dot{P}_a, \dot{P}_b\right]^T$$

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{\gamma}{M} & \frac{A}{M} & -\frac{\alpha A}{M} \\ 0 & 0 & f_a & 0 \\ 0 & 0 & 0 & f_b \end{bmatrix}$$

$$\mathbf{c} = [0, -F, g_a, g_b]^T$$

where x is the stroke of the actuator, P_a and P_b are respectively the air's pressure in the chambers A and B, F is the sum of the external forces acting on the piston along the x direction, M is the overall mass of the piston. The terms f_a, f_b represent the effects of the kinematics of the piston on the pressure gradients, while g_a and g_b represent the effects of the mass flow, like shown in the equations (6), (7), (8) and (9).

$$f_a(x, \dot{x}) = \frac{A\dot{x}n}{W_a + Ax} \tag{6}$$

$$f_b(x, \dot{x}) = \frac{\alpha A\dot{x}n}{W_b + \alpha A(L - x)} \tag{7}$$

$$g_a(G_a, P_a, x) = \\ = \frac{nG_a {P_0}^{1/n}}{\rho_0(W_a + Ax)P_a^{(1-n)/n}} \tag{8}$$

$$g_b(G_b, P_b, x) = \\ = \frac{nG_b {P_0}^{1/n}}{\rho_0[W_b + \alpha A(L-x)]P_b^{(1-n)/n}} \quad (9)$$

In these equations G_a and G_b are respectively the mass flow of the fluid entering or leaving from the chambers A and B, A represents the cross section area of the cylinder, W_a and W_b are the dead volumes, n is the index of the air's polytropic transformation and ρ_0 is the normal air's density. In this paper we have assumed for the air an isotherm transformation, so $n = 1$.

3 MULTIBODY IMPLEMENTATION

Given a multibody formalism based on a maximal cartesian set of coordinates, the state of the system is the vector of states of all unconstrained rigid bodies (this is the case of DAE approaches which introduce constraints with lagrangian multipliers).

Therefore, for a purely mechanical system without pneumatic actuators, the state is a vector like this:

$$\vec{y} = \{\vec{y}_{b1}, \vec{y}_{b2}, \ldots, \vec{y}_{bn}\}$$

where $\vec{y}_{bn}$ is the state of the n-th single body, that is $\vec{y}_{bn} = \{\vec{q}_{pos}, \vec{q}_{rot}, \dot{\vec{q}}_{pos}, \dot{\vec{q}}_{rot}\}$

Since each pneumatic actuator introduces new variables (namely, the pressures of the two chambers), the full state vector for a multibody system which includes also pneumatic devices must be the following:

$$\vec{y} = \{\vec{y}_{b1}, \vec{y}_{b2}, \ldots, \vec{y}_{bn}, \vec{y}_{C1}, \ldots, \vec{y}_{Cn}\}$$

where $\vec{y}_{Cn}$ is the pressure state of the n-th single pneumatic actuator, that is $\vec{y}_{Cn} = \{P_a, P_b\}$.

The main coordinate systems used as references for building the pneumatic actuator are shown in figure (3). Here $O1$ and $O2$ are the bodies connected by the cylinder; while P and S are the auxiliary coordinate systems which represent the anchor points of the actuator, and belong respectively to $O1$ and $O2$.

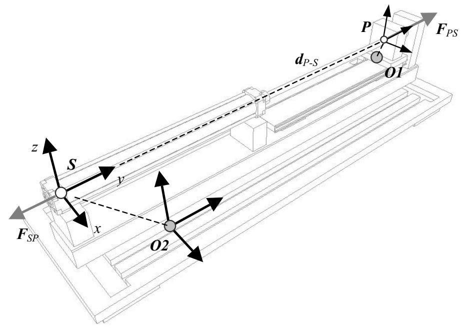

Fig.3: *Main references for the pneumatic "constraint object"*

Some auxiliary coordinates can be introduced:

$$\vec{d}_{ps} = \vec{P}_{o1} - \vec{S}_{o2}$$

$$\vec{D}_{ps} = \frac{\vec{P}_{o1} - \vec{S}_{o2}}{\|\vec{P}_{o1} - \vec{S}_{o2}\|}$$

where $\vec{d}_{ps}$ is the distance vector between the two constraint references, and $\vec{D}_{ps}$ is the versor which represents the direction of the actuator. These vectors must be updated when P and S move in space: this means that the actuator works as if it were linked to the bodies by means of two spherical joints at the end.

Note that the position and speed of the cylinder, named x and $\dot{x}$ in the state state vector of formulas (1), can be computed as:

$$x = \|\vec{d}_{ps}\|$$

$$\dot{x} = \left[\dot{\vec{P}}_{o1} - \dot{\vec{S}}_{o2}\right] \circ \vec{D}_{ps}$$

This means that position and speed of the actuator are functions of the mechanical state of the multibody system.

Given the previous definitions, at each integration step the pneumatic actuator can compute the forces $\vec{F}_{PS}$ and $\vec{F}_{SP}$ using simple formulas, knowing current state of pressures $\{P_a, P_b\}$. Forces are then applied to the rigid bodies $O1$ and $O2$ at points P and S (force directions are $\vec{D}_{ps}$ and $-\vec{D}_{ps}$).

Also, the integrator must be aware of the time derivative of the pressures, in order to integrate for new pressure-state $\{P_a, P_b\}$ of the cylinder. In fact $\{\dot{P}_a, \dot{P}_b\}$ are easily computed with eq.(1). It is important to stress that either for force computation, either for $\{\dot{P}_a, \dot{P}_b\}$, the knowledge of M is not necessary (mass of parts will play a role when integrating the remaining 'mechanical' part of the state, as in usual multibody methods). Note that in case of simulations of pneumatic cylinders with an average intake pressure of $600000Pa$, the integration of the equations of motion will surely require a very small time step, usually less than $0.001ms$ even with high-order integration schemes. This is expecially true if one needs to simulate also a closed-loop control for the actuator, and it is a consequence of the high stiffness in pneumatic phenomena resulting in rapid pressure oscillations.

For this reason, the simulation of complex devices for some seconds of working cycle may become very computationally-intensive, expecially considering that equations for the pneumatic are simple, but in the meantime all other equations, for the mechanical simulation of linked parts, may be really cumbersome. Therefore it is important to optimize the entire multibody code so that the simulation of articulated mechanisms won't require too much time even in case of many integration steps: we did so by means of our special solution scheme, described in [6], which shows a $O(n^1)$ solution time for n rigid bodies, compared to other Lagrangian methods which usually have an expensive $O(n^3)$ order.

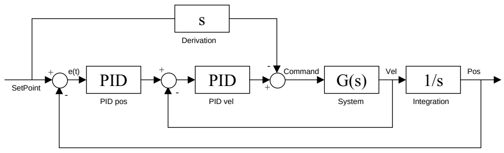

Fig.5: *Scheme of controller*

A special care has been put in creating a modular data structure for pneumatic actuators, so that they can be added, modified and deleted within the 3d interface with minimum user effort, even while the simulation is running (see figure 4). Since the control of pneumatic devices (for example via simulated 3/2 or 5/2 proportional valves) can be interesting for automation studies, we implemented an interface for scripting control. All variables of the cylinder, including valve controls, can be accessed with commands and programs written in *Javascript* language (ECMA-262 scripting standard, ISO-16262 specification). In this way the user of the software can write and run simple scripts which simulate specific control strategies, PID controllers, PLC programs, and so on.

4 CONTROLLER DESIGN

The implemented control scheme (fig. (5)) is based on the PID theory, consisting on two loops, the inner acting on speed and the outer acting on position. To this controller, we added an open speed loop acting in *feedforward* mode. We obtained experimentally the curve of piston's steady-state speed, as a function of valve opening. This experimental data is used to tune the *feedforward* contribute. The formulas used in our controller are based on the mathematical model of the pneumatic system.

Depending on the direction of the

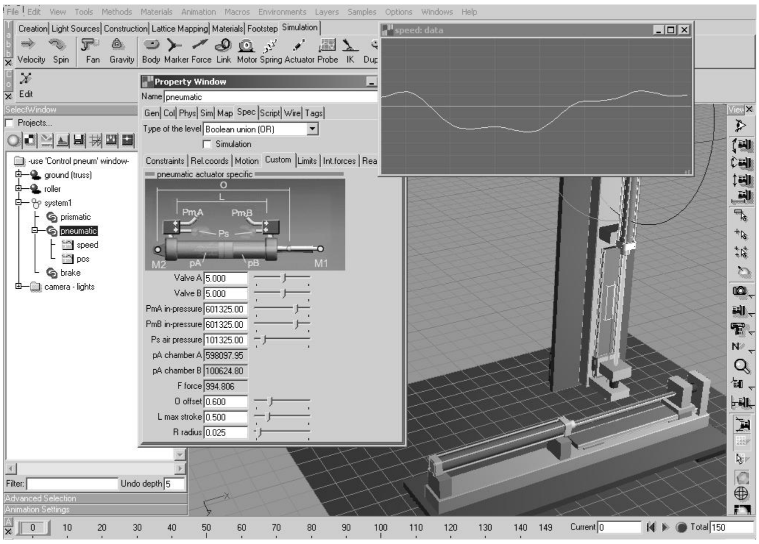

Fig.4: *Interface of our multibody simulation software*

movement of the actuator, different sets of constants for the PID controller have been used, for a total of 3 sets. The first set of constants is used for piston's shrinking, the second for expansion, the third is applied to the situation of zero speed. Customizing this latter set of values is mandatory if one wants to achieve an high stiffness of the robot in stationary conditions, and exploits very high values in PID constants.

In order to avoid the discontinuities caused by sudden activations of the *feedforward* effect, we decided to modulate such contribution as a function of the acceleration of the system: the *feedforward* effect works when the speed must change, but fades away when speed must be constant.

5 EXAMPLE

In order to validate our multibody method, we performed some simulations of our 3-DOF pneumatic robot *TORX* and compared the simulated results with the experimental ones.

This robot is based on parallel kinematics, using the 3-PUU scheme, and provides pure translation of the end effector by means of three vertical actuators [5]. In figure (6) one can see the six universal joints (*J1a, J1b, J2a, J2b, J3a, J3b*) and the three cylinders (*C1, C2, C3*) controlled by proportional valves.

The hardware control of the robot is PC-based: the signal coming from a linear encoder is processed by an encoder-counter board which is mounted on a commercial PC (550 Mhz Pentium III processor, 128 Mb RAM). Then, through another I/O board, an apposite analog signal is sent to a 5/2 proportional valve which feeds the pneumatic cylinder. The PC performs the closure of the control loop, thank to an operating system working in *hard real time* (RT-Linux V 2.2, a real-time release of Linux which easily allows a sustained thick of 0.001 s).

The simulation of the robot within our multibody software recreates the same type of control errors (see figure (7)), as a consequence of mechanical/pneumatic properties of the model.

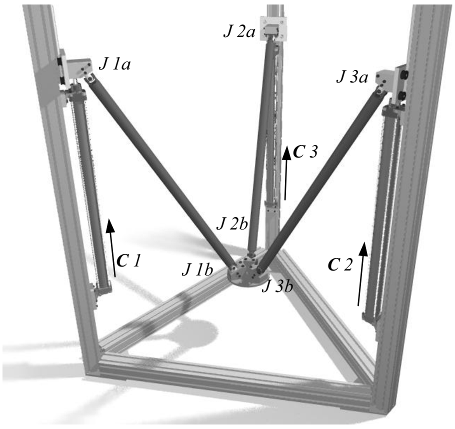

Fig.6: *Three-dimensional multibody simulation of TORX robot*

6 CONCLUSION

In this paper we explained the implementation of a pneumatic actuator model in our general-purpose multibody software, as a way to the simulation of pneumo-mechanical systems.

We adopted an object-oriented approach for the design of the data structures, hence obtaining a flexible and modular approach to the modeling of complex pneumo-mechanical devices, such as robots, where multiple pneumatic actuators can operate together.

Our multibody code has been validated through experiments performed on an experimental device which uses a single pneumatic actuator. These tests show a good agreement between computed results and experimental results.

As an advanced example of mechanism with multiple controlled pneumatic actuators, we performed the dynamical analysis of a 3-DOF parallel robot: given that our model takes into account the consequences of air compression with a high degree of realism, this method can be used to simulate the effect of pneumatic variables on the precision of the control.

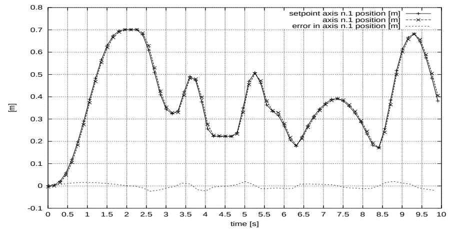

Fig.7: *Robot motion: experimental data*

REFERENCES

[1] X.Brun, M.Belgharbi, S.Sesmat, D.Thomasset, S.Scavarda, *Control of an electropneumatic actuator: comparison between some linear and non/linear control laws*, Journal of Systems and Control Engineering, 1999, pp. 387-406.

[2] ISO 6358, *Componenti attraversati da un fluido compressibile: Determinazione delle caratteristiche del fluido*,International Organization for Standardization, 1989.

[3] G.Belforte, T.Raparelli, M.Sorli, *Modelli di circuito con attuatori pneumatici*, AIMETA VII Congresso nazionale, 1984, pp. 485-498.

[4] G. Cusimano, H. Giberti, P. Righettini, *A two variable controller for servo pneumatic actuator*, 10th International WorkShop on robotics in Alpe-Adria-Danube region RAAD-2001, May 16-18 2001, Vienna, Austria.

[5] A. Tasora, H. Giberti, P. Righettini, *Design and experimental test of a pneumatic translational 3dof parallel manipulator*, 10th International WorkShop on robotics in Alpe-Adria-Danube region RAAD-2001, May 16-18 2001, Vienna, Austria.

[6] A.Tasora, *An optimized lagrangian multiplier approach for interactive multibody simulation in kinematic and dynamical digital prototyping*, VII ISCSB, Milano, 2001.