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Dynamic behaviour of pneumatic linear actuators☆

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ABSTRACT

The use of pneumatic linear actuators is generalised in engineering applications because of their many advantages, but modelling the force they supply may become more of a challenge due to their nonlinear behaviour and the hysteresis their energy losses cause. The authors propose a straightforward model to accurately predict force–displacement behaviour using as a basis experimental observations for several pressures and harmonic displacements of the rod. The model proposed includes two dissipative terms: one due to Coulomb friction and another due to structural damping. The force is proportional to relative pressure when acting as an actuator but nonlinear (modelled as a polytropic transformation) when acting as a pneumatic spring (with a closed pressurised chamber). The model accurately reproduces experimental results (Normalised Root Mean Square Errors lower than 2.5%) and may be used in control systems as well as in adaptive stiffness systems.

1. Introduction

Fields such as smart structures, robotics, or mechatronics are nowadays focusing on obtaining increasingly accurate designs for their actuators in order to fulfil requirements of high precision, light weight, etc. Smart actuators such as piezoelectric materials, magnetostrictive materials, shape memory alloys or magnetorheological fluids are being developed in order to address these challenges [1], though conventional actuators can also be useful if suitably characterised. That is the case of pneumatic actuators which, despite having been invented in the mid–twentieth century, have awoken a renewed interest in mechatronic applications in the last two decades.

Pneumatic Linear Actuators (PLA) are involved in a variety of industrial, automobile, aerospace, and marine applications. A typical PLA consists of a stationary cylindrical tube, a reciprocating piston and a rod. Airtightness is achieved by means of dynamic seals. These are usually made of thermoplastic materials and are able to undergo large deformations under a wide range of pressures, exerting contact pressure on the mating surfaces and avoiding the leakage of fluid. However, this component causes significant frictional forces and hence complicates the achievement of an accurate model for the PLA. Stribeck curves indicate that, for classical seals, friction at the seal–metal interface is directly proportional to speed and inversely proportional to load [2]. In addition, the sealing performance in terms of friction is dependent on the type of fluid, the geometry of the sealing interface, and the seal material. The case of rectangular seals under elastohydrodynamic lubrication conditions with uniform contact pressure distribution along the seal width has been studied by Nikas [3], and other studies have considered viscous heat generation for rotary seals [4]. Nevertheless, research is still weak on frictional or hysteretic aspects of pneumatic linear actuators.

Van Damme et al. [5] proposed a Preisach model in order to better determine the hysteretic behaviour, but their results were only accurate for a narrow range of displacements. Other authors used a Maxwell–slip model to reproduce the force–displacement hysteresis behaviour [6], or even the well–known generalised Bouc–Wen model [7], which shows lower RMS tracking errors when compared to the quasi–static Maxwell–slip model and the Prandtl–Ishlinskii model. An empirical approach, which turned out to be more accurate than most analytical alternatives, was carried out by Pujana-Arrese et al. [8] by means of fitting a fourth degree polynomial in which the coefficients varied linearly with pressure.

The importance of these models in pneumatic systems for different applications has been stressed by many authors. Barth et al. [9] present a PLA tracking sinusoidal inputs using a sliding control. Messina et al. [10] present mathematical dynamic models of positioner PLAs controlled by on–off solenoid valves. The nonlinear dynamics of this problem is due to its transient behaviour, but they achieved a mean positioning error of about 2 mm. Bone et al. [11] control the position of a novel hybrid pneumatic–electric actuator with inexpensive on–off solenoid valves. The addition of the DC motor connected in parallel is required to improve performance

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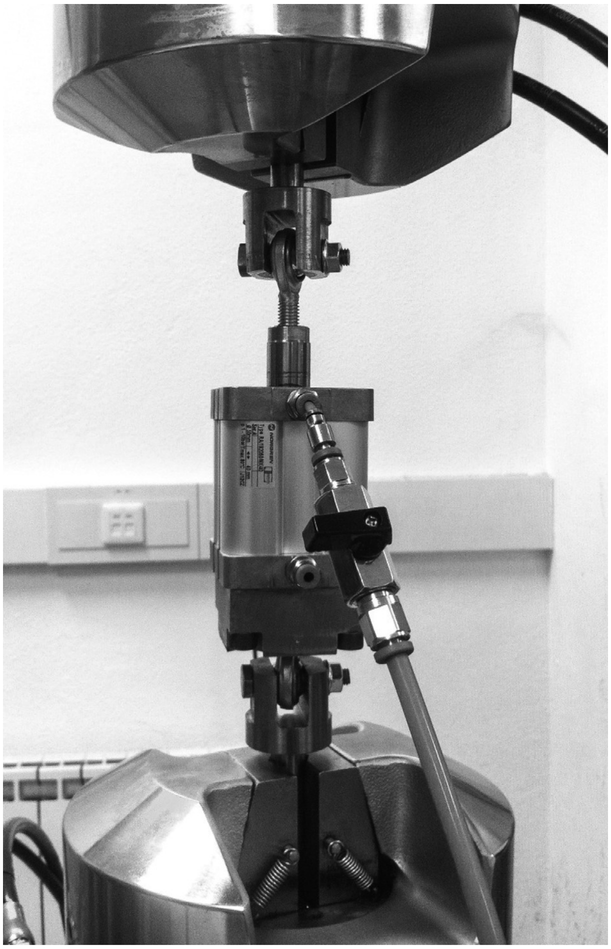

Fig. 1. Pneumatic linear actuator characterised for the case study.

and errors. Other authors present linearised PLA models where the parameters are estimated for different amplitudes of the input signal [12]. Nevertheless, there are still aspects that require further studies, especially those related to the transient phenomena due to the discontinuous nature of the on–off input and its influence on the dynamic behaviour of the PLA. In fact, many authors assume negligible dry friction in their control laws, which leads to unavoidable errors [13,14]. Others linearise Coulomb friction when modelling PLAs, but this strategy commonly leads to failure of the dynamic behaviour predictions [15].

Pneumatic linear actuators require a good hysteresis model which accurately simulates its force–displacement dynamic behaviour. In order to fill this gap, albeit partially, a nonlinear model for a pneumatic linear actuator is proposed in this study when used as a force actuator or as a pneumatic spring. It is simple, straightforward, easy to fit and useful for control purposes.

2. Characterisation of a pneumatic linear actuator

A double acting pneumatic linear actuator can behave either as pneumatic spring (by closing the pressurised chamber) or as an actuator (by supplying the required pressure). In the former case, the nonlinear behaviour of the pressure within the closed chamber and the dissipative forces need to be studied; in the latter case, pressurising and depressurising times may be measured and used in control systems.

Fig. 1 shows the double acting pneumatic linear actuator chosen to conduct the experimental studies. It is a commercial double–effect actuator with only one rod, model PRA/182050/M/40, manufactured by Norgren following the standard ISO 15552. The piston is 50 mm in diameter and the rod is 20 mm in diameter with a 40 mm stroke. Fig. 1 also shows how the actuator is attached to the hydraulic test machine. Both cylinder ends are attached to the hydraulic grips by means of spherical joints in order to avoid misalignment effects. The testing machine is equipped with a 10 kN full scale load cell and a LVDT with a calibrated displacement range of ±84 mm. Compressed air to feed the actuator is supplied by an air compressor equipped with a precision pressure–control valve. A valve is placed close to the chamber inlet port (the front chamber in the case of Fig. 1) so that the mass of air could remain constant during the test if required.

2.1. Characterisation as a pneumatic spring

The dynamic force exerted by the PLA when the rod is subjected to different harmonic displacements $d(t)$ and different initial pressures are set in either the front or the rear chamber, is characterised in this subsection. The pressurised chamber remains closed during the tests, so that the pressure (and hence the force) varies during the displacement cycle. The tests cover a combination of three displacement amplitudes D (3, 5, and 7 mm), five frequencies f (0.5, 1.0, 1.5, 2.0 and 4.0 Hz), and four initial gauge pressures P_0 (1, 2, 3, and 4 bar) for each chamber (front and rear) of the PLA

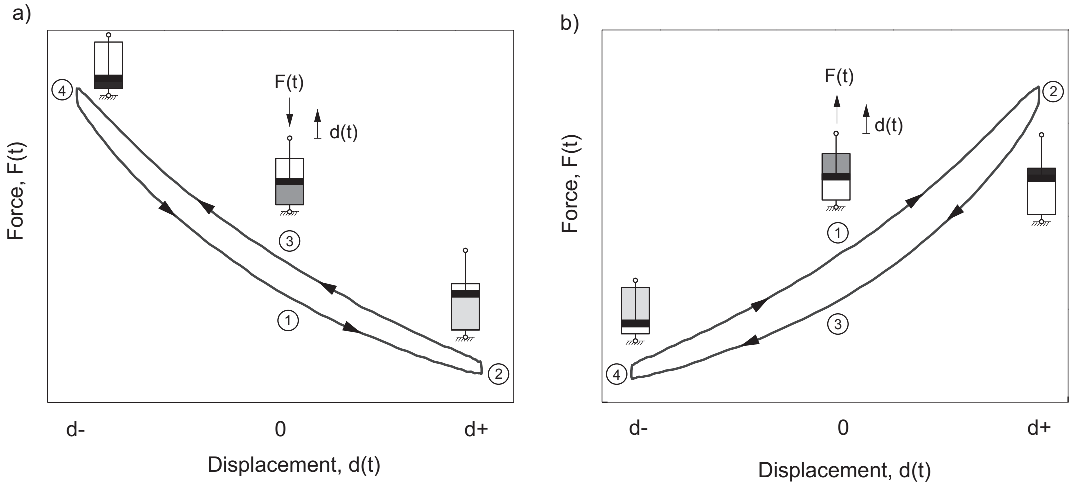

Fig. 2. Nominal shape of curves of a PLA: a) Rear chamber pressurised b) Front chamber pressurised.