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Research paper

A pneumatic actuator based on vibration friction reduction with bending/longitudinal vibration mode

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ABSTRACT

Piston–cylinder pneumatic actuators are widely applied in various fields of automation and robotics. The sealing rings comprised in these actuators unfortunately introduce friction and affect the positioning accuracy and output force. In this work, piezoelectric actuators are built in the pneumatic actuators to introduce vibrations with lower friction force. The friction reduction effect is compared between the bending vibration mode at a resonant frequency of 1.272 kHz and the longitudinal vibration mode at a frequency of 12.133 kHz. The pneumatic actuator has a bore diameter of 6.4 mm and a stroke of 13 mm. A static/dynamic friction force measurement system is established and the test results show a maximum 66.7% reduction of stiction force and a 50.8% reduction of dynamic friction force in bending vibration mode. And the friction reduction effect also happens in the longitudinal vibration mode, with a 47.4% reduction of stiction force and a 29.7% reduction of dynamic friction force.

1. Introduction

Pneumatic actuators are commonly applied in automation and robotics [1–4] due to their high force, relatively low manufacturing cost, clean operating conditions and high reliability [5–7]. The seals used in these devices plays a non-negligible role in the overall performance of the actuators. Typical pneumatic actuators comprise rubber rings to limit leakage, but they introduce non-linear friction and stick-slip phenomenon when the cylinder operates at a low speed [8,9]. This limits for instance the positioning accuracy of piston-cylinder pneumatic actuators.

There have been multiple methods to reduce friction force in piston-cylinder pneumatic actuators. For instance, dithering techniques were developed where a low amplitude and relatively high frequency periodic velocity signal is superimposed to the servo valve to improve pneumatic actuator friction characteristics [10,11]. Lubricants are improved, for instance by the addition of nano-particles [12]. Further, a new type of low friction cylinder using externally pressurized air bearings was developed to improve the friction characteristics of cylinder [13]. A multi-lobed seal was also developed for better friction characteristics in pneumatic actuators [14]. Finally, new liquid seal technologies using ferrofluids [15] or surface tension [16] were developed.

Alternatively, a method of reducing friction force by vibrations has attracted much attention in recent years [17,18]. It was observed that vibrating of one or two surfaces in contact dramatically alters their friction coefficient [19]. The experimental results of friction reduction induced by vibrations have been validated by a series of valuable investigations [20–25]. Most of them have some similar conclusions: the friction reduction has the best effect at resonant frequency vibration; a larger vibration amplitude produces a smaller friction force; and the vibrations from all directions to the sliding surface have friction reduction effect.

Similarly, the outside barrel of pneumatic cylinder was excited by ultrasonic transducer to reduce the friction. The frictional measurements revealed a 40% reduction at 31.65 kHz [26]. Afterwards, a longitudinal vibration mode pneumatic actuator was developed by screwing a transducer onto one end of the cylinder [27]. Then, a piezo-stack was integrated onto the piston of pneumatic actuator to generate a longitudinal vibration along piston movement direction [28]. In the following research, a design which integrates two piezoelectric stacks in a self-made pneumatic cylinder is proposed. This actuator with a bore diameter of 5 mm and a stroke of 10 mm showed a 52% reduction from the original friction force at a driving frequency of 18.29 kHz with a bending vibration mode [29].

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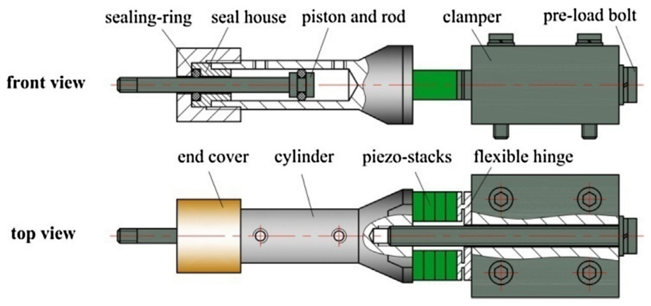
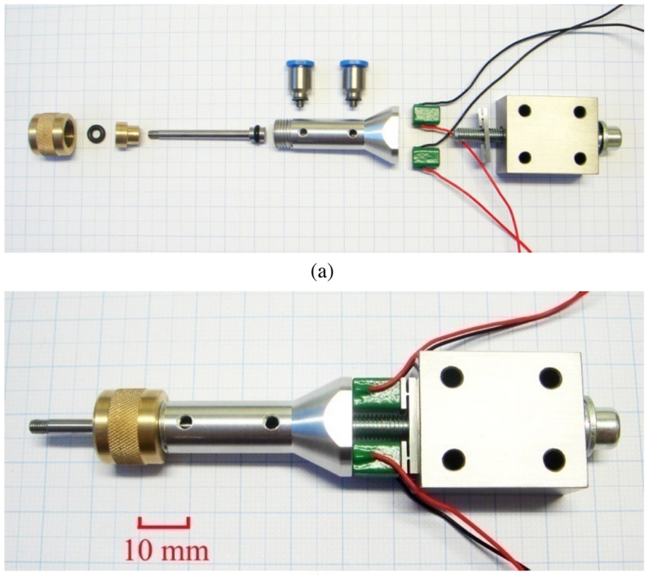


Fig. 1. Schematic of the pneumatic actuator prototype (front view and top view).



(a)

(b)

Fig. 2. (a) Each part of the prototype (before assembling); (b) Picture of the prototype assembly.

In this paper, the design of a dual-mode pneumatic actuator is firstly presented, followed by the description of the static/dynamic friction measurement system and the operation process. Next, tribological characteristics measurements are performed and the discussion is shown on the results.

2. Actuator structure and measurement system

The pneumatic actuator prototype developed in this paper mainly consists of a cylinder (aluminum) with a bore diameter of 6.4 mm, a seal house and end cover(brass), a piston and rod (rod diameter: 3 mm), two sealing rings (TRELLEBORG, NBR, OD: 6.46 mm, ID: 2.9 mm), two piezo stacks (PIEZOMECHANIK, size: $5 \times 5 \times 9\,\text{mm}^3$, max stroke: 9 μm, R-frequency: 100 kHz), a flexure hinge (steel), a clamper (steel), and a pre-load bolt (steel). The H-shaped flexure hinge is used to accommodate misalignment between the piezoelectric stacks and the cylinder. This avoids stress concentration, and hence improves the lifetime. The piezo stacks are preloaded by a bolt through the cylinder, the H-stock, and the clamper. As can be seen from Fig. 1, two flat parallel surfaces are manufactured on the cylinder body, and the distance between the two flat surfaces is the same as the thickness dimension of the clamper in order for an easier assembly to the piezo stacks' preloading.

For a better view of the prototype, the separated parts and the assembly pictures are shown in Fig. 2.

It has been shown from the previous references that pneumatic actuators with different vibration modes have been investigated separately, but few scholars have ever tried several modes in a single prototype. This is also one of the targets of the current research. The actuator design used in this research is using two piezo-stacks located at the base of the cylinder. As is illustrated in Fig. 3(a), a bending vibration mode as calculated by finite element simulations for the prototype can be gained when the two piezo-stacks are driven with a phase difference of π, thus one of the stacks will expand while the other is shrinking. Consequently, a first order bending mode vibration happens as the clamper is fixed by four bolts, and the cylinder can be seen as a cantilever beam. In this case, the rubber rings comprised in the cylinder has a vibration direction perpendicular to the motion of the piston. Inversely, a longitudinal vibration mode for the prototype is easily to be generated as the piezo stacks are excited with the same phase, as is shown in Fig. 3(b). And the rubber rings of the actuator have a vibration direction parallel to that of the piston motion.

The frictional experiments in this paper are carried out on a tribometer, which is able to perform accurate displacement and instantaneous friction force measurements. The measurement system is mainly consisted of a voice coil linear motor (Unite Precision Mechanical Technology VCAR0436-373, with Elmo controller), a force sensor (ZHONGNUO, ZLBS-50N, resolution: 0.025 N), a laser displacement sensor (ZSY, ZLDS100-500-125, resolution: 1 μm), a data acquisition card (National Instruments, USB-6211), a vibration power supply (QD-8C), a flexible coupling, a mounting block and the prototype. As is shown in Fig. 4, the functional elements of the apparatus are decoupled by utilizing a self-made flexible coupling screwed between the force sensor and the piston rod, in order to have a better elimination for the misaligned error.

The motion of the piston is generated by the voice coil linear motor which allows to generate a frictionless and stable motion. The active coil of the linear actuator, which acts as the movement source is fixed to a connecting part which can slide back and forth on a guide rail, and the force sensor fixed between the connecting part and the piston rod to record the friction force. The experimental setup picture is shown in Fig. 5.

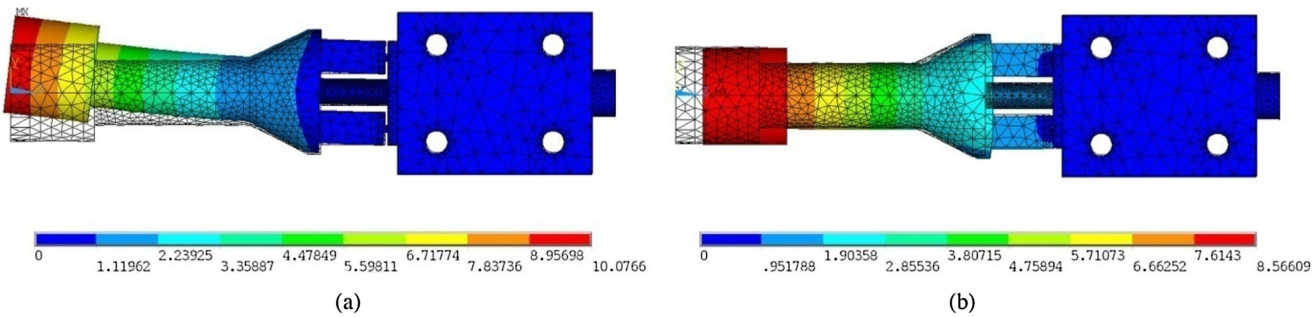


Fig. 3. (a) Bending vibration mode of the pneumatic cylinder model; (b) Longitudinal vibration mode of the pneumatic cylinder model.

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