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Low power linear actuator for direct drive electrohydraulic valves

Yong LI[1], Fan DING[1], Jian CUI[1], Qi-peng LI[†‡1,2]

([1]*State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University, Hangzhou 310027, China*)

([2]*School of Mechanical and Automobile Engineering, Zhejiang University of Science and Technology, Hangzhou 310023, China*)

[†]E-mail: lqp@zju.edu.cn

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Abstract: This paper presents a bi-directional permanent-magnet linear actuator for directly driving electrohydraulic valves with low power consumption. Its static and dynamic performances were analyzed using the 2D finite element method, taking into account the nonlinear characterization and the eddy current loss of the magnetic material. The experiment and simulation results agree well and show that the prototype actuator can produce a force of ±100 N with the maximum power being 7 W and has linear characteristics with a positive magnetic stiffness within a stroke of ±1 mm. Its non-linearity is less than 1.5% and the hysteresis less than 1.5%. The actuator's frequency response (−3 dB) of the displacement reaches about 15 Hz, and the most significant factor affecting the dynamic performance is identified as the eddy current loss of the magnetic material.

Key words: Electrohydraulic valves, Linear actuator, Low power, High pressure, Positive magnetic stiffness
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INTRODUCTION

With the rapid development of electrohydraulic control technology, electrohydraulic valves, especially servo and proportional valves, have been used in many different applications, such as machine tools, motor drives, forges, ships and aircrafts. As a systematic philosophic consideration of fluid power driven technology and control technology in general engineering, there is a trend towards a reduction in the power consumption of the actuator for electrohydraulic valves by improving efficiency (Lu, 2005). Through advances in high-energy permanent magnet materials like neodymium-iron-boron (NdFeB), a range of compact and high-performance linear actuators for direct drive electrohydraulic valves are now available. Moog Inc. (1998) presented a permanent magnetic differential linear actuator which provides numerous benefits over conventional solenoids including more efficient magnetic flux patterns, thus producing greater driving force, less current required and bi-directional operation but, since affected by variations in the airgaps, large non-operating airgaps are required to achieve linear characteristics within a stroke of less than ±1 mm, so its energy consumption reaches about 30 W, which also leads to a complex design for thermal diffusion of the coil. Besides, acting as a negative magnetic stiffness, the permanent magnets tend to force the armature apart from its central position, which brings about instability and thus requires mechanical springs to maintain normal operation. Evans *et al*.(2001) presented a permanent-magnet linear actuator which has a large positive magnetic stiffness by using an optimized structure, but the energy transfer efficiency is relatively low, which will consume more power in order to produce a large driving force. Furthermore, low power actuators such as micro actuators (Girbau *et al*., 2007) and switch actuators (YUKEN Inc., 2002) have been reported, whereas low power linear actuators for direct drive electrohydraulic valves have not been proposed yet.

‡ Corresponding author

This paper is concerned with the design and analysis of a low power linear actuator for high-pressure applications. Both the numerical simulation based on the 2D finite element method and the experimental analysis are presented, and the results indicate that the prototype actuator consumes less power than a comparable actuator, with equivalent output capability.

ACTUATOR DESCRIPTION

The actuator (Li *et al.*, 2007) investigated has the cylindrically symmetrical configuration shown in Fig.1. It consists of two annular permanent magnets and a coil. The stator, the sleeve and the armature make up the magnetic paths together with the permanent magnets. The sleeve is split into four parts by three non-magnetic separating rings, forming a trapezoidal pole head and two basin-shaped pole heads, and the armature is cut with three annular grooves corresponding to the axis positions of the three pole heads. As welded together to form a whole, the sleeve can prevent the coils from contacting the oil, and the actuator can work under high fluid pressures. In particular, smaller axis non-operating airgaps are designed in the actuator compared to the MOOG actuator referred to (MOOG Inc., 1998), in order to improve energy transfer efficiency.

The permanent magnets provide a constant polarizing magnetomotive force (MMF) and, due to thesymmetric configuration, this force tends to restore the armature to its central position or force the armature apart from its central position. When direct current with one polarity is applied to the coil, the coil produces a control MMF that increases the airgap flux at one polarizing path, and reduces it at the other. This imbalance forces the armature to move in the direction of the stronger flux until the force is re-balanced. Similarly, by changing the polarity of the current applied to the coil, the armature will move in the opposite direction.

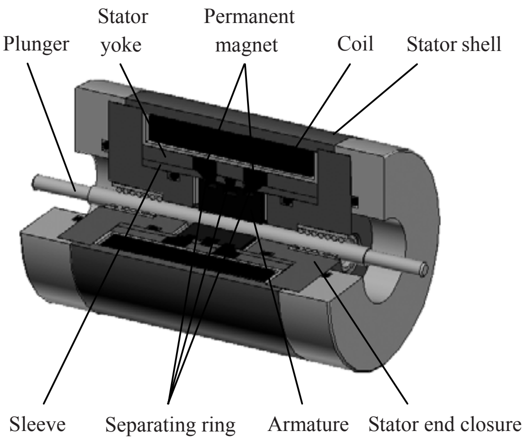

Fig.1 Structure of the actuator

ACTUATOR MODELING

To ensure a high force/current ratio, high-energy NdFeB permanent magnets with a remnant flux density of 1.23 T, a coercive force of 890 kA/m and a relative permeability of 1.1 were chosen. As the actuator is probably operated in a partially saturated condition, the nonlinear characterization of the magnetic material of the widely applied pure iron should be included in the numerical simulation.

Magnetic field analysis

Neglecting the displacement current and the hysteresis, the field governing equation in terms of the magnetic vector potential, derived from Maxwell equations, is

$$\nabla \times \frac{1}{\mu} \nabla \times \boldsymbol{A} = \boldsymbol{J}_{\mathrm{S}} - \gamma \frac{\partial \boldsymbol{A}}{\partial t} + \nabla \times \boldsymbol{H}_{\mathrm{C}}, \tag{1}$$

where $\boldsymbol{J}_{\mathrm{S}}$ is the source current density, $\boldsymbol{A}$ the magnetic vector potential, $\boldsymbol{H}_{\mathrm{C}}$ the coercivity of the permanent magnets, μ the permeability, γ the conductivity.

Kinematics analysis

The governing equation for the motion of the armature is

$$F = M \frac{\mathrm{d}^2 x}{\mathrm{d}t^2} + K_{\mathrm{d}} \frac{\mathrm{d}x}{\mathrm{d}t} + Kx + F_{\mathrm{L}}, \tag{2}$$

where F is the overall force produced by the polarizing and control MMF, M the armature mass, K_{d} the damping coefficient, K the spring constant, F_{L} the load force, x the armature displacement from its central position of Fig.1.

Electrical analysis

The governing equation for the electrical circuit is

$$u = Ri + \frac{\mathrm{d}\psi}{\mathrm{d}t}, \tag{3}$$

where u, i and R are respectively the control winding voltage, current and resistance, and ψ the magnetic flux linkage of the coil.

To predict the static and dynamic characteristics of the actuator, the mathematical model for the actuator is established combining Eqs.(1)~(3), and has been solved by using the 2D time-stepping finite element method, taking into account the nonlinear characterization and the eddy current loss of the magnetic material. Here we omit the details of the computational method, which is referred to (Woo and Kwon, 2004).

SIMULATION ANALYSIS

Static analysis

Based on the 2D finite element computation, the static force-versus-displacement characteristics of the prototype actuator could be obtained using Maxwell's stress tensor, and the simulated results are shown in Fig.2 for currents of −0.8 A, −0.4 A, 0 A, 0.4 A and 0.8 A. The armature force remains almost linear over the whole range of ±1 mm, and includes the creation of a positive magnetic force, tending to restore the armature to its central position, with the magnetic paths formed by the enhancive structure of trapezoidal pole heads and grooves.

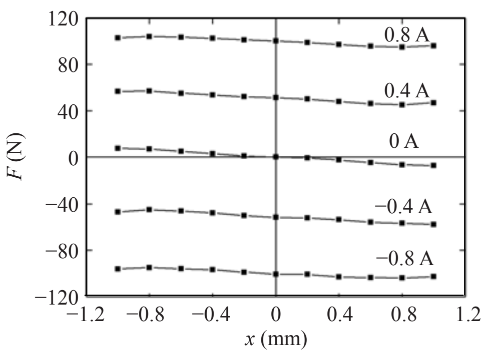

Fig.2 Static force-versus-displacement characteristics

Dynamic analysis

The simulated frequency response of the actuator is shown in Fig.3. It can be seen that the frequency response (−3 dB) of the displacement reaches about 15 Hz. The dynamic performance is generally affected by the iron loss and the mechanical response. As the mechanical response can be calculated from Kinematics Analysis formula ($f=(K/M)^{0.5}/(2\pi)$) to be about 200 Hz, the dynamic performance of the actuator is mainly affected by the iron loss. Owing to its cylindrical symmetry, the magnetic structure cannot be laminated, resulting in a noticeable eddy current loss which occupies most of the iron loss (Clark *et al.*, 2003). Furthermore, we carry out a comparison by assuming a low conducting material with conductivity of 1.0×10^6 S/m which is only about one tenth that of pure iron used in the modeling. Then we find the consequent frequency response (−3 dB) of the displacement reaches about 100 Hz as shown in Fig.3. Therefore, it can be concluded that the dynamic performance of the actuator is mainly affected by the eddy current loss of the magnetic material.

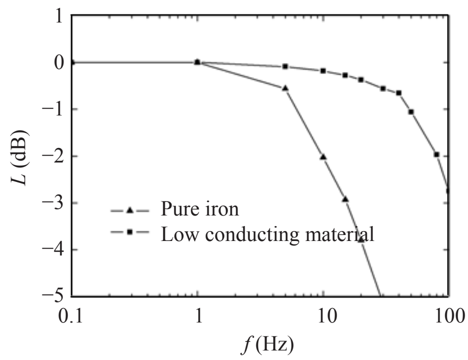

Fig.3 Simulated frequency response of the actuator adopting two different magnetic materials

EXPERIMENTS

The construction of the experimental system is illustrated in Fig.4. The function generator generates a direct current (DC) or sine wave control signal input to the constant-current power amplifier that provides an exciting current of ±4 A for the actuator. Two springs with the stiffness of 50 N/mm are conjunct to transform the driving force of the actuator into displacement measured by a linear variable differential transducer (LVDT) displacement sensor with a ratio of precision of 0.2%, and a measuring range of 4 mm.

Static results

The static characteristics of the actuator are shown in Fig.5. Experimental results are in agreement with the simulated ones, the actuator's non-linearity is evaluated to be less than 1.5%, and the hysteresis is evaluated to be less than 1.5%, too. The maximum power consumption can be calculated to be 7 W at a driving force of ±100 N.

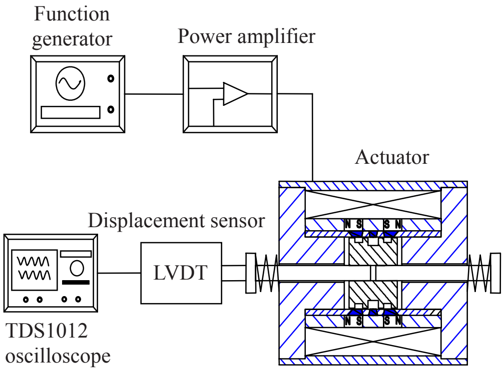

Fig.4 Schematic of the experimental system

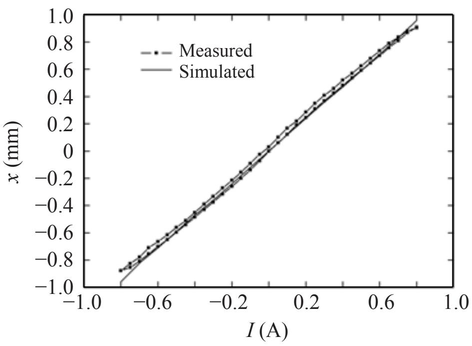

Fig.5 Comparison between the simulated and experimental static results

Dynamic response

The frequency response of the actuator is shown in Fig.6. Agreement of the overall behavior is observed between the experimental and simulated results, and the frequency response (−3 dB) of the displacement reaches about 15 Hz.

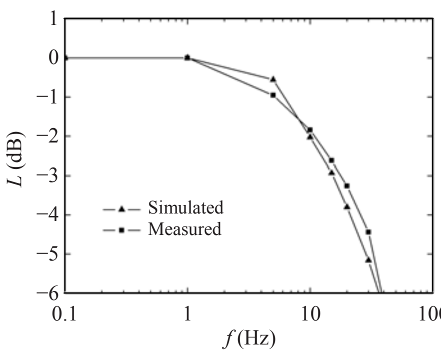

Fig.6 Comparison between the simulated and experimental frequency response characteristics

CONCLUSION

A low power linear actuator for high-pressure applications is presented. The experimental and simulated results agree well and show that the actuator can produce a force of ±100 N with the maximum power of 7 W and has linear characteristics with a positive magnetic stiffness. Furthermore, the most significant factor affecting the dynamic performance is identified as the eddy current loss of the magnetic material. Therefore low conducting magnetic materials should be applied to suppress the effect of the eddy current loss and, with the explosive development of magnetic materials like soft magnetic composite (SMC) (Dou *et al.*, 2007), it is possible to further improve the actuator's dynamic performance.

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