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Hydraulic amplifier design and its application to direct drive valve based on magnetostrictive actuator

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ABSTRACT

A new type of direct drive valve based on giant magnetostrictive material is designed. Comparing to traditional servo valves, the frequency response is improved with a considerable flow rate. A hydraulic amplifier with flexible pistons is applied on the designed valve; its structure is optimized through elasticity mechanic theory, finite element method and CFD method. The valve is modeled in AMESim and a prototype is produced. Through simulation and experiments, the bandwidth of the designed valve is above 100 Hz while its flow reaches 30 L/min.

1. Introduction

Electro hydraulic control system, with merits of wide bandwidth, large overloading, high energy density has attracted attention extensively in modern aeronautical industry and vehicle industry. Electro hydraulic servo valve (EHSV), regarded as the bridge between electric and hydraulic system, is considered as the crucial part of the whole system. While on the other hand, the reliability of EHSV is doubted as it is very sensitive to the oil pollution [1].

Direct drive valve (DDV) is a new type of servo valve, as the spool connects directly with the driver, own properties of fast response, insensitive to oil pollution and low hysteresis, DDV is considered as the trend of EHSV development. Series of companies and organizations have taken efforts in developing DDV products meeting civil and military requirements. The electro-mechanical transmission equipment is the crucial component for a DDV. There are varies types of DDVs, which can be classified by their electric–mechanic devices [2]. The DDV developed by Moog Inc. based on a moving iron linear motor, could reach a flow of 40 L/min in 50 Hz under system pressure of 35 MPa [3]. Wu Shuai developed a DDV based on triple-redundant voice coil motor (VCM) and optimized based on PSO method [2]. Grunwald and Olabi designed two types of pressure control arrangements based on magneto-rheological fluid (MRF), namely: MR-Orifice and MR-Valve, and the MR-Valve exhibits a better performance in holding the pressure without a significant leakage [4–6].

In recent years many intelligent materials are applied in design of DDV, giant magnetostrictive material (GMM), with the properties of fast response, great energy density and high Curie temperature [7], giant magnetostrictive actuator (GMA) is an application of GMM which could produce tiny displacement signal very precisely, since 1990s, GMA finds its prospects in fields of flow control, active vibration control and precision machining [8], especially in designing of the high speed servo valve working in high frequency circumstance. Compared with traditional actuators and other smart materials, the advantages of GMA for driving DDV lies in following aspects.

- Comparison with traditional actuators

(i) Compared with torque motor actuator

The GMM actuator (GMA) owns a far more extensive bandwidth than torque motor: learned from tested results, exciting signal from 5 Hz to 1000 Hz could be transformed into mechanical vibration through GMA, while the traditional torque motor, with large inertia, usually fail to reach 100 Hz [9].

(ii) Comparison with VCM

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Table 1
Technology features of smart material overview.

Typical features	PZT	GMM	SMA
Elongation	0.1%	0.2%	5%
Energy density	2.5 kJ/m^3	20 kJ/m^3	1 kJ/m^3
Bandwidth	100 kHz	10 kHz	0.5 kHz
Hysteresis	10%	2%	30%
Magnetic/electric-mechanic coupling coefficient	0.5–0.6	0.7–0.75	
Curie temperature	200–300 °C	380 °C	

Compared with VCM, GMA performed a much larger thrust [2,10]. As the hydraulic force and elastic force in DDV is large and arises considerably with increasing frequency and flow rate, the thrust of actuator should be large enough to drive spool. Also, VCM occupies more space and is more complex in structure. GMA helps to form a compact and simple structure, expending the application range of DDV and improving its reliability.

- Comparison with other smart materials

Properties of smart material which owns the potential of applying into actuator design [11] is listed in Table 1 for a simple comparison.

(i) Comparison with SMA

A shape memory alloy (SMA) is a material that can return to its original shape above the phase transformation temperature after a large deformation, learned from Table 1, its bandwidth is limited and hysteresis is quite large, also as it is usually driven by temperature [12,13], which is not so easy to be controlled in industry environment.

(ii) Compared with PZT actuator

Piezoelectric (PZT) actuator is an alternative of GMA, while it is also limited by the thrust, according to Table 1, with much less energy density, the PZT actuator produce a force much smaller than GMA in equal stroke, learnt from Section 4, the force requirement of DDV is about 120 N, which means that the actuator should produce a force larger than 1000 N before hydraulic amplifier. Compared with PZT, a GMM actuator also enjoys a very low driving voltage [2,13,14], thus the safety of working environment is guaranteed.

However, though a GMA owns many merits in applying in DDV design, its stroke limits the flow rate of servo valve. As the GMM-DDV designed in literature [2,15], the stroke of spool is only 50 μm, the flow rate is 2 L/min. Thus, corresponding amplifier should be employed to enlarge the stroke of GMM in a relative extensive bandwidth.

There are two categories of displacement amplifiers: mechanical and hydraulic. The mechanical amplifier based on stacking or levers with flexure-hinges has been studied and used widely [16,17]: a bridge type mechanical amplifier is designed by Shen [18] used in amplification of PZT driver of DDV and the flow rate reaches 5.9 L/min in 80 Hz; Lindler designed a DDV based on lever amplifier, the flow rate reaches 9 L/min, in a bandwidth of 300 Hz [19]; a GMM Nozzle flapper valve based on bridge-type amplifier developed by Karunanidhi [9] has reached a flow rate of 8 L/min. Hydraulic amplification is achieved by pistons of different areas: with GMM bar driving the large piston and the power output delivered by small driven piston. Comparing with mechanical amplifier, these structures produce considerable displacement with limited space occupied; hence this amplification method is more attractive for servo valve design. Yoon [20] developed a PZT actuator based on hydraulic amplifier and the impact of friction and oil compression is studied. Ushijima and Kumakawa developed a PZT actuator for adaptive powertrain mounts with hydraulic amplifier the actuator reaches a stroke of 70 μm [21]; Shibayama developed a PZT actuator using sealed hydraulic amplifier, the stroke reaches 0.3 mm [22]; Chakrabarti [23–25] designed a GMM actuator based on hydraulic amplifier with a stroke of 1.6 mm in 20 Hz.

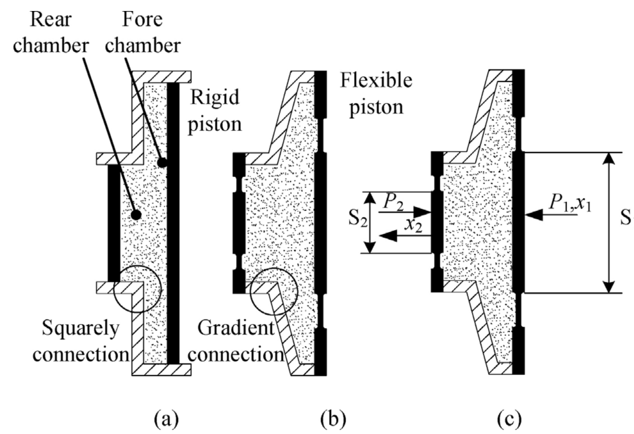

Fig. 1. Traditional and proposed hydraulic amplifier.

Traditional hydraulic amplifier [25] is shown in Fig. 1, the piston is rigid; fore and rear chambers are squarely connected.

There are limits lie in the above structure: friction between piston and chamber; disclosure of oil; inertia of piston; the flow resistance increases due to squarely connection, contraction flow phenomenon usually happens around the squarely connection; oil trapped occurs because of the limited axis length of fore chamber.

In this paper, to modify the hydraulic amplifier structure, a kind of flexible piston based on flexure film and a gradient connection between fore and rear chambers is designed. With the flexible piston introduced, friction is avoided, disclosure is greatly reduced and the dynamic load is relieved. The gradient connection can reduce the flow resistance and relieve the impact of oil trap due to the sudden change of flowing area. The modified hydraulic amplifier is shown as Fig. 1(b).

The objective of this study is to develop a GMM-DDV with hydraulic amplifier. The magnetic and dynamic model of GMM driver is established in Section 2; the structure of hydraulic amplifier is designed and optimized based on elastic small deflection theory, finite element method (FEM) as well as CFD method in Section 3; the valve structure is designed and the total driving force is calculated in Section 4. The model of whole GMM-DDV is established in AMESim and a prototype is produced, the simulation and experiment result is shown in Section 5. Finally, some conclusions are gained in Section 6.

2. Design of GMA

2.1. Configuration of GMA

The configuration of GMA could be distinguished into three categories by the location order of GMM (T), coil (C) and permanent magnet (M), the properties of different configurations are explained in literature [11]. The layout of GMA in DDV is a TCM structure, which means that GMM bar is located in the center and then comes the coil, the permanent magnet is surrounded outside. This structure balances the structure complex and field inhomogeneity, and a high energy density is gained [8].