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Design and experimental study of a novel giant magnetostrictive actuator

Guangming Xue [a,*], Peilin Zhang [a], Zhongbo He [a], Dongwei Li [a], Yingjie Huang [a], Wenqiang Xie [b]

[a] *Vehicle and Electrical Engineering Department, Ordnance Engineering College, Shijiazhuang, 050003 China*
[b] *Cadre Rotational Training Brigade, Ordnance Engineering College, Shijiazhuang, 050003 China*

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ABSTRACT

Giant magnetostrictive actuator has been widely used in precise driving occasions for its excellent performance. However, in driving a switching valve, especially the ball-valve in an electronic controlled injector, the actuator can't exhibit its good performance for limits in output displacement and responding speed. A novel giant magnetostrictive actuator, which can reach its maximum displacement for being exerted with no bias magnetic field, is designed in this paper. Simultaneously, elongating of the giant magetostrictive material is converted to shortening of the actuator's axial dimension with the help of an output rod in “T” type. Furthermore, to save responding time, the driving voltage with high opening voltage while low holding voltage is designed. Responding time and output displacement are studied experimentally with the help of a measuring system. From measured results, designed driving voltage can improve the responding speed of actuator displacement quite effectively. And, giant magnetostrictive actuator can output various steady-state displacements to reach more driving effects.

1. Introductions

As a kind of functional material, giant magnetostrictive material (GMM) has many useful characters in driving an actuator, just as high Curie temperature, high magneto-mechanical coupling coefficient and large generated stress et al. These advantages help the giant magnetostrictive actuator (GMA) stand out from some other actuators [1]. By employing good performances of GMM, GMAs have shown their important applications in driving electro-hydraulic servo-valves [2–4], vibration control [5–9], energy harvesting [10–12], active mounts [13,14], driving mirrors [15] and some other areas [16–18].

A typical GMA is shown in Fig. 1. The coil generates driving magnetic field for the giant magnetostrictive rod (GMR) with the help of inputted electric signals. Preload spring guarantees the GMR in compressed state and pushes the output rod to initial position with power off. Bias magnet provides bias magnetic field for GMM. The bias magnetic field is always set at the center position to achieve higher strain growth rate. Simultaneously, the linear relationship between the magnetostrictive strain and excited magnetic field is quite good under this bias position. In addition to these required parts, a cooling waterway is necessary for the GMA sometimes [1].

Though in different detailed structures, actuators applied to different areas have the same working principle shown in Fig. 1. For the bias magnetic field, GMR is in the middle length between the longest and shortest state when the coil is not energized. So the GMR can elongate or shorten under electric signals with positive or negative directions, and then the actuator can output displacements in different directions. This double-direction output design is applicable to most conditions while not suitable to the double-state switching valves. That is because a switching valve requires only one direction displacement or force, and the double-direction output actuator must waste a half of its displacement. What's more, the displacement in the unneeded direction, if occurs, will attack other parts in the valves.

Take the ball-valve in an electronic controlled injector for example to show suitable structure for GMA. Current electronic controlled injector is normally closed and its working principle can be shown in Fig. 2. With no power, the actuator is in the longest state and the steel ball is pushed by the actuator to make the ball-valve closed. When power is on, axial dimension of the actuator shortens to open the ball-valve. Then with the fuel pressure in the control chamber declining, high-pressure fuel pushes the needle valve matching parts open and the injector starts spraying. Under circumstances like this ball-valve, one-direction displacement is just needed and the direction is that the actuator shortens when energized. Traditional actuators cannot meet this requirement.

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* Corresponding author.
E-mail address: yy0youxia@163.com (G. Xue).

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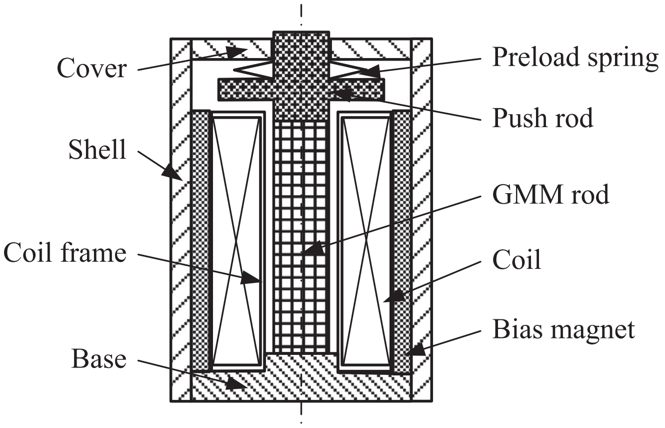

Fig. 1. Typical structure of a GMA.

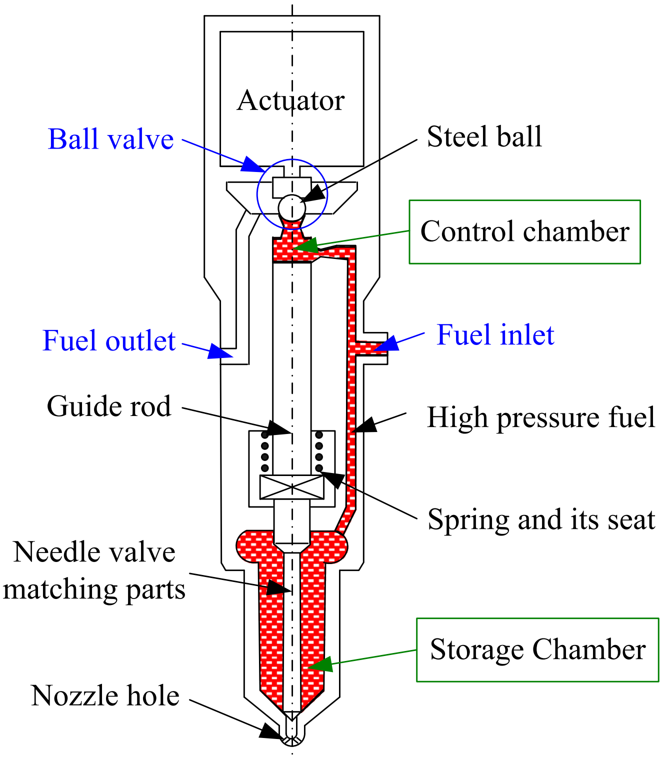

Fig. 2. Working principle of an electronic controlled injector.

Many researchers have focused on the application of the GMA to driving the electronic controlled injector, while they have neglected this point and their researches are in concept design or just typical actuator studying [19–25]. Xue et al. have designed a strongly biased actuator, in which the elongation of GMR can be converted to shortening length of the actuator [26,27]. Its working principle and limits will be discussed in Section 2.

Another point requiring cared is the responding speed of the whole actuator. GMA's responding speed may be not as fast as expected even responding time of the GMM is quite little. From inputting voltage, the whole process including forcing effective current, stimulating magnetic field and producing mechanical strain. And the most time is spent on forcing current within the coil as the induction is so high to guarantee enough high magnetic field. Even if GMM can reach very short responding time of microsecond order of magnitude, the whole outputting time, about several milliseconds, is quite long. This conclusion could be proved by measured or calculated results in references [3,17,19,28–32]. Such long responding time of the GMA will cause the switching valve working abnormally and restrict applications of the GMA.

Actually, electro-magnetic actuator has faced the same problem as both two type actuators employ a high-induction coil to generate magnetic field. For electro-magnetic actuators, increasing opening voltage is another effective way to saving responding time of the coil current. This action could also be introduced to the GMA [33–35]. Xue et al. have referred the driving waveform applied to the electro-magnetic field and reached a waveform suitable to the GMA in a simulation way [36,37]. However, some important design and conclusions should be determined by experimental results.

In this paper, design concept of the GMA suitable to an electronic controlled injector (or other high-speed switching valve) is presented at the first time. To obtain higher output displacement, the GMR is biased non-magnetically. And a novel output rod is employed to acquire displacement in certain direction. Then a new input voltage which can save opening time of the actuator's displacement is presented and its detailed information was determined experimentally. Furthermore, driving effects on the coil currents and actuator's displacements are also studied experimentally.

2. Structure design

2.1. Design concept

For the ball-valve of an electronic controlled injector, axial dimension of its driving actuator should be shortened to the minimum length when energized. That is to say, the giant magnetostrictive actuator should satisfy two requirements before being applied to these types of switching valves. Firstly, giant magnetostrictive material should reach maximum output in only one direction (shortening or elongating). Secondly, deformation of the material should be transferred to the shortening amount of the actuator.

Bias magnetic field exerted on the GMM has decisive impact on the deforming direction of GMM. The relationship between magnetostrictive strain and external magnetic field is shown in Fig. 3. If biased in middle position magnetically, GMM can but output only a half of the maximum strain in one direction, no matter how high current is exerted on the coil. So for a typical GMA, more material will be needed to reach desired strain and the strain in the other direction will be wasted.

A reasonable design for GMA is exerting strong bias field for the GMM. Under this condition, GMM is in a relatively high length without power. Combined with the current in negative direction shown in Fig. 3, magnetic field within GMM decreases and the

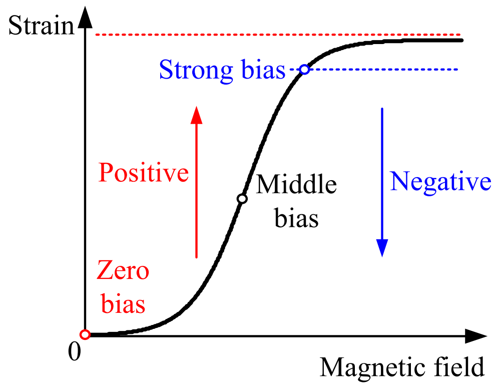

Fig. 3. Strain-magnetic field curve of GMM.