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Displacement model and driving voltage optimization for a giant magnetostrictive actuator used on a high-pressure common-rail injector

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ABSTRACT

A novel giant magnetostrictive actuator driving the ball-valve of a high-pressure common-rail injector was designed in this paper. With the help of a special output rod, elongation of the giant magnetostrictive rod was converted to shortening of the actuator. So the actuator could suitable to a normally-closed injector. The traditional series equivalent circuit of the coil in the actuator was modified, and then the displacement model of the actuator was established and solved by a numerical method. The voltage, coil current and displacement of the actuator were acquired by a dedicated measuring system. Then the model was validated under the input voltages using sinusoid, AC square and DC square waveforms. A new driving voltage waveform suitable to the actuator was designed. And then the designed voltage was optimized for short responding time and slight fluctuation of the actuator displacement. The residual displacement caused by the hysteresis of giant magnetostrictive material was also considered.

1. Introduction

Giant magnetostrictive material (GMM) is a kind of functional material and has many effective features in driving an actuator, just as large displacement, high Curie temperature, large generated stress (force). The material is always manufactured into shaft or film form, and then outputs large displacement and force with the help of some other necessary components just as a coil and preloading spring etc. To meet certain requirements, the giant magnetostrictive actuators (GMAs) are designed in plenty of forms [1]. Due to its good performance and abundant structure forms, the GMA has many important applications as driving electro hydraulic servo valve [2,3], controlling vibration [4–7], developing rotary-linear motion [8], ejecting high-viscosity fluids [9], active powertrain mounts [10], driving segmented mirrors [11], realizing power and information transmission [12] and some other areas [13,14].

Driving the electronic controlled injector using GMM is also a significant research direction. Traditional electromagnetic actuator can't meet the fast responding requirement any more. And currently, piezoelectric actuator is applied to control the common-rail injector. The piezoelectric actuator performs well in precise motion control, quick response and miniature size. However, it will lose its piezoelectric properties under overstress or overheating. Furthermore, small displacement and force is disadvantaged for a large injection flow [15]. So some scholars researched the approach to driving the electronic controlled injector by the GMM.

Li et al. [16] designed a GMA for fuel injector by finite element analysis and experimental research. Danescu et al. [17] optimized the magnetostrictive injection actuator by inputting square waves in two different duty cycles. Bright and Garza [15] found that high compression could lead to high speed for better combustion control. Bright et al. [18] also designed a magnetostrictive transducer used as a programmable fuel injector and tested its transient-state displacement response of the transducer. Wang et al. [19] designed a GMA used in automobile engine fuel injection system and modeled its displacement from the coil current. Fuzai Lv [20] designed a high-speed powerful solenoid based on GMM. With a deforming beam amplifying 5.1 times of the GMM rod elongation, the actuator could output displacement of 0.15 mm. Rongge Yan [21] designed a giant magnetostrictive fuel injector and used finite element method analyzing its magnetic field. They calculated the actuator's displacement and concluded that the relationship between the coil current and the output displacement is approximately linear. Tanaka et al. [22] developed a common-rail proportional injector driven by tandem arrayed GMA. The actuator used a Z-shaped holder coupled 6 GMM rods into 2 sets, and then could output double displacement of the output of one rod. The length of each rod is 30 mm while the actuator could stretch 50 μm displacement. They also gave the experimental results of the transient-state process.

Above giant magnetostrictive actuators exhibited some advantages in special circumstances, while are hardly applied to the current electronic controlled injector. The current high-pressure common-rail injector is normally closed and its working principle is shown in Fig. 1. The key point for injection is controlling the fuel pressure difference between the control chamber and storage chamber by driving the actuator in an electromagnetic, piezoelectric or magnetostrictive type.

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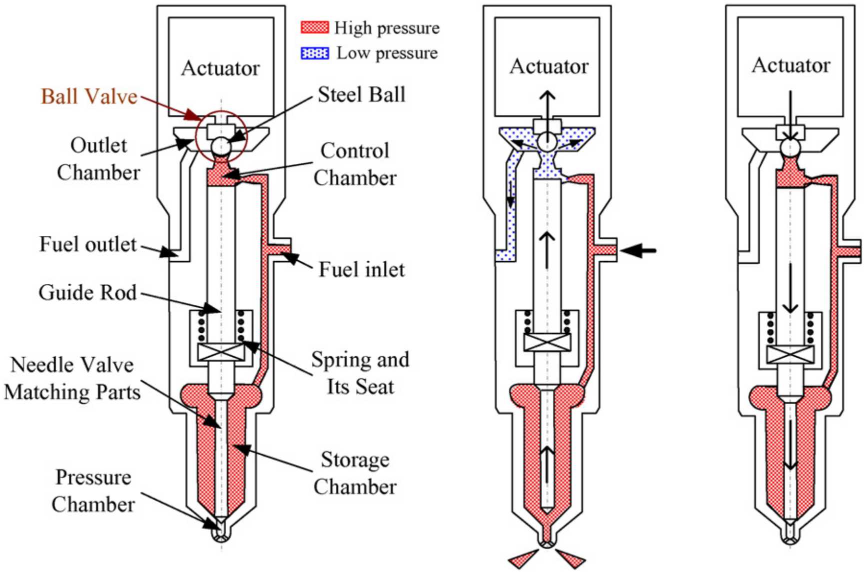

(a) Not energized (b) Power on (c) Power off

Fig. 1. Working principle of a high-pressure common-rail injector.

(a) Without being energized, the actuator is in the longest state and steel ball is pushed by the actuator to make ball valve normally closed. The control chamber and storage chamber are both filled with high-pressure fuel.
(b) When power is on, the actuator shortens to move the steel ball upward. The fuel pressure in control chamber reduces quickly to a relatively lower value while the pressure in storage chamber keeps high. Then the needle valve matching parts, spring seat and guide rod are pushed upward as one part and the injector begins injecting. It is noted that the actuator should output the displacement or force quite fast, or the pressure difference between the two chambers won't be instituted.
(c) When the power is off, the actuator moves the steel ball downward and the ball valve is closed. The fuel pressure in the control chamber will build up until reach high pressure again. The needle valve matching parts, spring seat and guide rod move to their initial positions and the injector stops injecting.

So, the actuator suitable to a high-pressure common-rail injector must be in longest-state without any input. When electrified, the actuator shortens in dimension to open the ball-valve of the injector. If the actuator were elongated, the output rod must hit the other component of the ball-valve. The described actuators above didn't have this character and then couldn't be applied to the kind of injector. We have designed a GMA with a strong bias magnetic field [23]. With the signal in certain direction input, the strongly biased actuator could convert the elongation of GMM rod into shortening length of the actuator and could be applied to the normally closed injector. However, as the bias magnetic field was not so strictly exerted, the actuator couldn't keep shortening with arbitrary input.

Another problem is that the transient-state displacement response of GMA is not focused on adequately. Most researchers modeled the displacement from the coil current while rare scholars cared about the method of improving the responding speed of the current. Though responding time of the giant magnetostrictive material is little, the rise time of the coil current is quite long, and so responding speed of the actuator is not as fast as expected. The driving voltage for the actuator used on an injector is a square waveform. For generating enough magnetic fields, the coil induction is always on the mH order of magnitude. Such induction of the coil would lead to long rise and fall time even after controlled, which may even cause the injector working abnormally. The long responding time could also be proved by the experimental or calculated results in some references [8,11,16–18,24–26]. Actually, a common point between GMA and electromagnetic actuator is that they all employ a coil to generate the magnetic field. So some methods used on the electromagnetic actuator can be referenced to the GMA after being modified [27–29].

Furthermore, the giant magnetostrictive material has a hysteresis phenomenon, which will lead to residual displacement of the actuator after power off. Measured results by Grunwald and Olabi, Fig. 27 in Reference [24], could also prove existence of the residual displacement. If the residual displacement amplitude were too high, the ball-valve can't close stably. So the residual displacement should be calculated or measured to see if the GMM should be demagnetized in each cycle.

A GMA applied to the high-pressure common-rail injector is designed in this paper. By using a novel output rod, the actuator reaches the goal of shortening only under arbitrary input signal. The equivalent circuit of the coil is modified and can calculate the responding time more effectively. Then the displacement of the actuator considering the transient-state process is modeled. The model is verified with the help of an experimental system. Referring to the driving voltage of the electromagnetic actuator, the driving voltage waveform suitable to the GMA is designed. And based on the model, the driving waveform is optimized. From computing, the driving voltage can improve the transient-state performance of the actuator. At last, the residual displacement is calculated and analyzed.

2. Structural design of GMA

Structure drawing of the giant magnetostrictive actuator used on the high-pressure common-rail injector is shown in Fig. 1. Cap and output rod are in threaded connection and move as one part. The thick part of output rod is slotted, then the output rod has relative shift with the still block axially. The pre-pressure on the giant magnetostrictive rod is supplied by the spring and can be adjusted through tightening or unscrewing the screw thread between nut and shell. The giant magnetostrictive rod is not biased magnetically.

The washer and still block keep unmoved all the time. With the coil electrified, the giant magnetostrictive rod outputs driving force