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Theoretical and experimental investigations of the temperature and thermal deformation of a giant magnetostrictive actuator

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ABSTRACT

Giant magnetostrictive actuators (GMAs) have received considerable attention in recent years and are becoming increasingly important in the exploitation of new type electromechanical devices. The performance of giant magnetostrictive actuator (GMA) is generally determined by the precision of the GMA output displacement; however, the heat-induced displacement of a GMA is the principal element influencing the precision of the GMA output displacement. In this paper, a precise GMA with a heat-induced displacement suppression system is developed; the heat-induced displacement control mechanism consists of a temperature control module and a thermal displacement compensation module. Based on the heat-transfer rules, a GMA heat-transfer mathematical model and a GMM rod heat-induced displacement model are built; next, the mathematical models of GMA heat-transfer are solved and the temperature distribution, the heat-induced displacement, and the heat transfer rate of GMA are completely obtained. Finally, a test system for a GMA heat-induced displacement suppression system is implemented, and an experimental study of the system is performed. The results of the GMA heat-induced displacement by experimental research basically coincide with the results of the GMA heat-transfer mathematical model, that is, the GMA temperatures are controlled to below 35 °C and the GMA heat-induced displacement remains within a small range under an input current of 1 A for a period of continuous operation of 80 min. The system observably improved the precision of the GMA output displacement; as a result, the research results provided a basis for a precise micro-displacement GMA.

1. Introduction

Giant magnetostrictive materials (GMMs) dubbed Terfenol-D enabled the development of a totally new class of electromechanical devices with higher energy density, faster response, and better precision than previously possible [8,14,15,18,19,21,31,32]; such devices can be applied for use in sound and vibration sensors [22], sonar systems [13], active vibration control systems [32], micromotional control [20], magnetostrictive motors [10,20], hydraulics [5,12,23,24], and sensors [6]. Magnetostrictive devices are fairly robust as far as wear and tear are concerned, which exhibit their potential for replacing traditional piezoelectric devices.

Giant magnetostrictive actuators (GMAs) are one of the most exciting new actuator technologies available today, which have created new design options for mechanical and electrical engineers alike; however, GMAs are complex structures requiring a careful design, with the performance of a GMA determined directly by the precision of the GMA output displacement, which is dependent on the coupling deformation displacement due to magnetostrictive deformation and thermal deformation. Therefore, determining how to decouple, inhibit, and control the thermal deformation displacement are the difficult points and key technologies required for improving the precision of the GMA output displacement.

For high-power GMAs, forced cooling measures or constant temperature control methods are common approaches to achieve a GMA high-precision output displacement, which uses water circulation between the GMM rod and the exciting coil to remove the heat generated by the GMM rod and the exciting coil and, accordingly, to ensure the GMM rod temperature accurately remains within a certain small range. For example, Jia [7] cooled the GMM rod using a spiral water cooling tube outside of the GMM rod. Lu et al. [16] adopted the internal and external double water cooling mechanism to further reduce the thermal displacement to 0.02 μm. Wang [24] developed a type of the real-time compensation system based on a thermal compensation pipe, which uses hydraulic oil as a cooling medium to cool the GMM rod; they performed experiments both in summer and winter, and the experiment results indicated that the GMM rod temperature rise is rapid at the

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beginning, but after the temperature rose to a certain value, it tended to reach equilibrium, and the system achieved a relatively satisfactory thermal displacement control effect. Furthermore, the phase change temperature control method [4], which keeps the GMM rod temperature constant by using some phase change materials to absorb or release a large amount of latent heat in the process of phase change to enable the GMM rod temperature remains nearly unchanged. Anjianappa applied this method to attempt to maintain the temperature of the GMM rod in a certain range; however, because of the limitation of the heat absorption capacity of the phase change materials, the GMM rod temperature can only remain constant over a short time. The subsequent improvement method is called the combined temperature control method, which uses both water or semiconductor material and phase change materials to cool the GMM rod, in other words, the water on the outside of the coil is used to prevent thermal deformation of the shell, and the phase change materials on the inside of the coil is used to inhibit thermal deformation of the GMM rod. Wu performed an experiment [26] that indicated if no cooling measures were taken, the temperature of the GMM rod would exceed 100 °C in the fourth hour when the GMA begin working, but by using the combined temperature control measures, the GMM rod temperature can be maintained to within 45 ± 0.5 °C, during which time, the output displacement of the GMM rod caused by the temperature fluctuation is not more than 0.1 μm. Semiconductor refrigeration is a method that involves the contact surfaces being coated with thermal silicone grease to increase the coefficient of thermal conductivity [9] of the surface in contact with several semiconductor thermopiles that are installed on both ends of a coil bobbin to enable cooling water to flow past the hot end of thermopile, which can strengthen the radiating effect and ensure that there is a higher cooling efficiency. Kwak [27] used a compressed air to cool the GMM rod; through a finite element analysis and experiment research, they concluded that a cooling air temperature of 18 °C and an air velocity of 2.8 m/s represent the optimal cooling conditions.

For a small power GMAs, the passive thermal deformation compensation method often is used, mainly including the software compensation method, the thermal expansion offset method, and the flexible support compensation method. The software compensation method is simple to use [29]. In the GMA using the software compensation method, the temperature control component is installed on the GMM rod, and the controller is used to compensate the heat-induced displacement of GMM rod; the GMA does not require additional hardware system, but its heat-induced displacement control precision is not high. The thermal expansion offset method [28] in a precision GMA with 20 μm stroke and a 1 mm × 1 mm × 20 mm GMM rod is placed on the stainless steel coil bobbin, which has the same thermal expansion coefficient as the GMM rod. The external surface of the GMA uses an invar alloy that has a very low thermal expansion rate, so the GMM rod thermal deformation is offset by the stainless steel coil bobbin thermal elongation. The basic idea of flexible support compensation is to utilize the GMA coil bobbin thermal expansion to drive a flexible hinge mechanism, which adjusts in real time the position of the GMM rod bottom support point, thus inhibiting the GMA heat-induced displacement output during GMA operation. Xia [25] designed a flexible hinge compensation device with a supply current of 600 mA; after continuous application of the power supply for 120 min, the thermal deformation of GMA was up to 27 μm without compensation, but the thermal deformation reduced to 7 μm after compensation.

For theoretical research of the GMM rod thermal deformation and the heat-induced displacement control, Zeng et al. [30] used the finite element method (FEM) to calculate the flow field distribution and temperature field distribution of the GMA with a forced cooling system; the cooling system was able to keep the temperature of GMM rod under 70 °C. Stillesjo [3] analyzed the operation of a giant magnetostrictive ultrasonic transducer with a drive current 10 A and frequency of 21 kHz using FEM, and he concluded that the flow rate of the cooling water of 6.8 L/min can keep the temperature of actuator at approximately 80 °C. Li [12] designed a control valve driven by a hollow giant magnetostrictive actuator; in the hollow actuator, the hole is used as a cooling passage to cool the actuator in addition, they studied the change of the GMA temperature as a function of the driven frequency and analyzed the eddy current loss, magnetic hysteresis loss and frequency characteristics of the complex permeability based on the theory of the minimum energy condition and magnetism theory [11]. Anjanappa and Bi [1], Bi [2], Angara [17] proposed a thermal resistance theory that was applied to research on heat transfer and amended the piezomagnetic equation; unfortunately, the deduction of the GMA calculation model on the heat-induced displacement was not performed.

In summary, although there are many compensation structures and control methods to control the GMAs thermal deformation, the effect is not ideal enough to only adopt a single thermal compensation approach, and the existing GMAs thermal displacement control research is mainly in the experimental study phase, with a lack of systematic theoretical research on the GMA heat transmission and heat-induced displacement compensation mechanism. Therefore, it would be of great theoretical and engineering significance to explore the GMA thermal displacement control theory and perform an experimental study of the combination of temperature control and heat-induced displacement compensation.

The thermal displacement control methods above-mentioned are constant temperature control method and passive thermal deformation compensation method, respectively, for the former, the equipment is complex and the real-time temperature control performance is not always satisfactory; for the latter, the coefficient of thermal expansion for the compensating element varies with temperature, so it is difficult to keep the high precision of the thermal deformation compensation in a large temperature range. In this paper, we present a new idea that active and passive control method simultaneously, that is, we reduced the temperature of GMM rod to a small temperature range by means of active control method, obtained a high thermal displacement control precision by use of passive control method, which is easier to achieve in a small temperature range for a GMA. In the present study, a GMA is designed and fabricated with a heat-induced displacement suppression system, which consists of an active GMM rod cooling module and a passive heat-induced displacement compensation module. Next, based on the equivalent thermal resistance theory and the definition of the liquid specific heat capacity, the GMA heat-transfer model at steady-state is established. Subsequently, assuming the coefficient of thermal expansion of the GMM rod is constant, the GMA heat-induced displacement calculation models under both free convection and forced convection are determined. Accordingly, the temperature rise, the heat-transfer rate, and the heat-induced displacement of the GMM rod are calculated according to the present calculation model. Finally, the heat-transfer test system of the GMA is built, and the test results have a good agreement with the theoretical calculation results of the present model, which provides a great contribution to the design and application of a precise GMA.

2. GMA structure and working principle

As Fig. 1 shows, the GMA magnetic circuit is composed of the following components: output shaft, upper end cover, GMM rod, sliding block, preloaded bolt, outer cover, base, etc. By adjusting the preloaded bolt, a appropriate prestress (7 MPa is selected from the