Active Noise Control System for Ultracompact Electric Vehicles Using Giant Magnetostrictive Actuator: Fundamental Consideration on Comparisons of Two Types of GMAs Built on the FEM Analysis on the Magnetic Flux Density

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Abstract. Regarding with creation of interior acoustic control system for the ultracompact electric vehicle, it is necessary to select the device that output sound wave. We have been studying on interior acoustic control system for the next-generation mobility using the giant magnetostrictive actuator (GMA). In this paper, we conducted basic study to design the GMA applying proposed interior acoustic control system that we analytically investigated the characteristics of the magnetostriction force when the giant magnetostrictive materials were deformed by a magnetic field using electromagnetic field analysis. In this analytical study, we conducted the magnetostriction force for changing frequency ranges of piezoelectrically controlled amplifiers using FEM of the GMA. From the results, when we used the GMA for proposed interior acoustic control system, the GMA has sufficient output performance of control sound wave by ANC for low frequency noise such as road noise from 100 to 500 Hz. However, we need to consider changing the actuator's size, weight, shape, and components, as well as changing to a material with higher magnetic permeability to output a wider range of frequencies such as music.

Keywords: Giant Magnetostrictive Actuator, FEM, Magnetostriction Characteristics.

1 Introduction

The control system including the sensor and actuator using the giant magnetostrictive material (GMM) has been researched and actively developed [1]-[3]. GMM changes sharply due to the magnetic field from outside. The feature of the GMM is high-speed response and high-output energy more than other functional materials [4]. From now on, to apply the giant magnetostrictive actuator (GMA) to more control systems, it is necessary to design the GMA and GMM according to the system. We have been studying interior acoustic control systems for next-generation mobility using the GMA [5]-[7]. In this paper, we conducted a basic study to design the GMA applying the proposed ANC system that we analytically investigated the characteristics of the thrust when GMSs were deformed by a magnetic field using electromagnetic field analysis.

2 Proposed interior acoustic control system for ultracompact electric vehicles using GMA

2.1 Interior noise of the ultracompact EV

In recent years, One- or two-seat ultracompact electric vehicle (EV) have been developed as shown fig. 1. However, ultra-compact EVs have yet to reach a notable expansion in use. Ultracompact EVs are compact and lightweight bodies. Therefore, the rigidity of the outer plate is low. Because of this low rigidity, the road noise generated by the tires and the wind noise generated from the projection shape of the vehicle is transmitted to the cabin [8]-[10]. In a general vehicle, sound-absorbing materials are installed inside the vehicle for soundproofing. Luxury vehicles have an active noise control (ANC) system that controls a sound-generating speaker, which is installed in the cabin. However, it is difficult to install sound-absorbing materials or an ANC system in ultracompact EVs, given the limited interior space. The demand for ultracompact EVs is expected to increase in the future, while research and development into noise control systems as noise countermeasures have been insufficient.

2.2 New system that provides an interior acoustic environment suitable for passenger preferences

Traditional countermeasures of interior noise for vehicles have been to create a quiet interior environment. To create a quiet environment in an interior space, we typically use passive noise control using sound-absorbing materials or ANC by outputting sound waves that are in the opposite phase to the noise [12]-[15]. However, we considered that a quiet environment is not an optimal interior environment for passengers. Therefore, we proposed a new interior acoustic control system for the ultracompact EV [5]-[7], [16]-[18]. The feature of this system, this system can provide a quiet environment through noise redaction and pleasant sound by masking. Fig. 2 shows the proposed interior acoustic control system. This system can switch a noise reduction by ANC and masking depending on the condition of the passenger. The condition of the passenger is judged by the

Fig. 1. Ultracompact EV

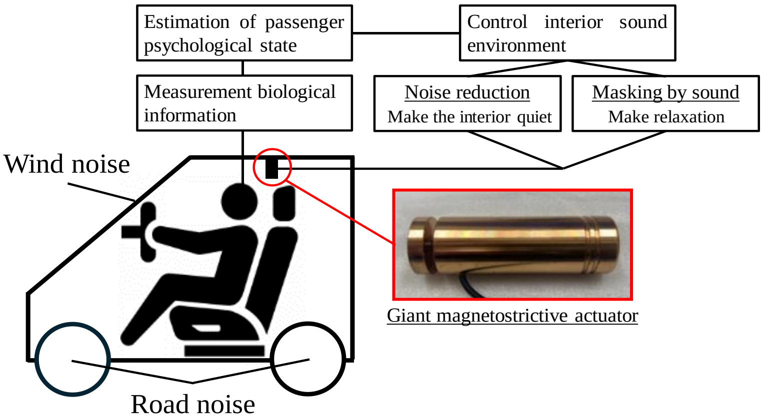


Fig. 2. Proposed interior acoustic control system for the ultracompact EV using a GMA.

Fig. 3. Biological measurements such as brain waves and heart rate.

biological measurements such as brain waves and heart rate as shown in fig. 3. Feed-backed measured data to the system, switching a noise reduction by ANC or masking improves the interior acoustic environment. In this system, the control sound and sound signal of masking are output from wall surface vibration by GMA which is installed in

Fig. 4. GMA installed a wall or flat plate part in the cabin.

Table 1. Comparison with GMM and piezoelectric material characteristics

	Giant magnetostrictive material (Terfenol-D)	Piezoelectric material (PZT)
Method of shape change	External magnetic field	Applying voltage
Response speed	～100 μs	0.1～1 ms
Possible to output frequency range	～High frequency	～Ultrasound
Energy density	14×10^3 ～ 19×10^3 J/m^3	0.6×10^3 ～ 1.6×10^3 J/m^3
Distortion	1400 ppm	140 ppm

the cabin as shown in fig. 4. However, GMA ideal for the interior acoustic control system of the ultracompact EV has not been developed. In this paper, as a basic study for GMA development, we analytically investigated the characteristics of the thrust when GMMs were deformed by a magnetic field using electromagnetic field analysis. We focused on low-frequency noise reduction by ANC and clarified the difference in the magnetostriction force when outputting a single frequency of 100 to 500Hz, which is the frequency band of road noise, depending on the shape of the GMM.

3 GMM Attracting Attention as Smart Materials

Materials whose functions change depending on the surrounding environmental conditions are called smart materials. GMM is one of the smart materials. GMMs are materials whose magnetic material changes when a magnetic field is applied to them. GMM is high-speed response and high Curie temperature. And it is possible to contactless magnetic field control [4], [19]-[20].

Table 1 shows the comparison with GMM and piezoelectric material characteristics. In this table, GMM is Terfenol-D and piezoelectric material is Lead zirconate titanate

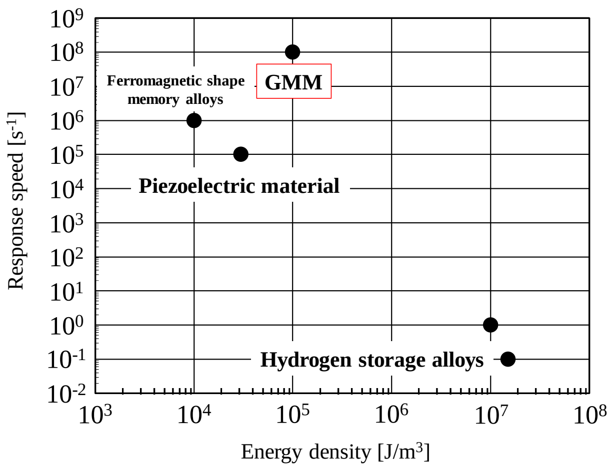


Fig. 5. Relationship between the response speed and the energy density for the various functional materials including the GMM.

(PZT). First, regarding with method of shape change, the GMM changed the shape by an external magnetic field. On the other hand, the PZT has changed the shape by applying voltage. Second, regarding response speed, both GMM and PZT are lower than 1 ms. In addition, they can output from low to high frequency. However, the energy density of GMM is more than 12 times bigger than PZT. Therefore, GMM has a larger work per unit volume than PZT. Furthermore, the distortion of GMM is also more than 10 times bigger than PZT. Therefore, the actuator using the GMM has higher output energy than PZT when we consider an actuator that generates vibration.

Fig. 5 shows the relationship between the response speed and the energy density for the various functional materials including the GMM. The GMM has high response speed and energy density compared to PZT and Ferromagnetic shape memory alloy. Furthermore, when we compared shape memory alloys, hydrogen storage alloys, and GMM, both shape memory alloys and hydrogen storage alloys have higher energy density than GMM. But response speed is slower than GMM. For many reasons, the actuator using GMM has high responsibility and energy density.

4 How the GMA works

In this section, we indicated the structure of the magnetic bias method GMA and magnetostriction force. Fig 6 shows the cross-section of the GMA along the longitudinal direction. The GMM is comprised of columnar GMM, three permanent magnets that apply a biased magnetic field, a solenoid coil, and two spacers. The GMM stretches in the direction of the magnetic field. Therefore, the GMA also stretches in the direction of the axial direction. Fig. 7 shows the GMA, GMM, and permanent magnet. Next, we explain the magnetostriction force from the GMM when a current flows through

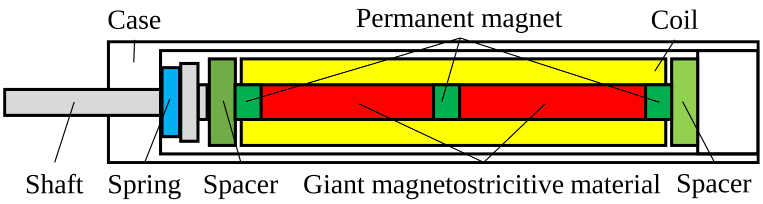


Fig. 6. Cross section of the GMA.

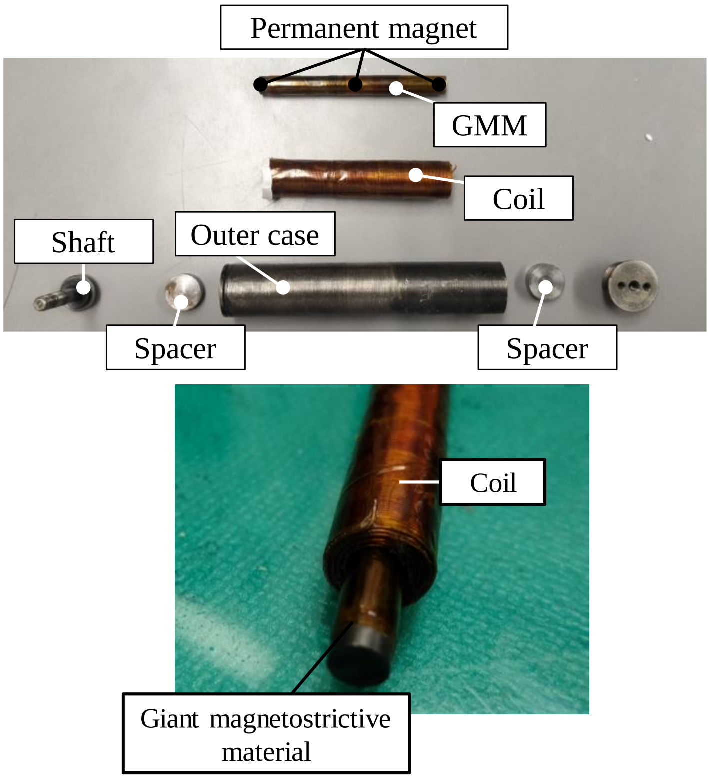


Fig. 7. Interior components of the GMA.

the solenoid coil including GMA. Fig. 8 shows the relationship between a current flow through the solenoid coil and magnetostriction force. There are some permanent magnets for the bias in the GMA. Therefore, the GMM outputs the steady magnetostriction force by the magnetic field from the permanent magnet even when there is no current flowing through the coil. Then, when there is current flowing through the coil, the magnetostriction force increases or decreases according to the magnitude of the current.

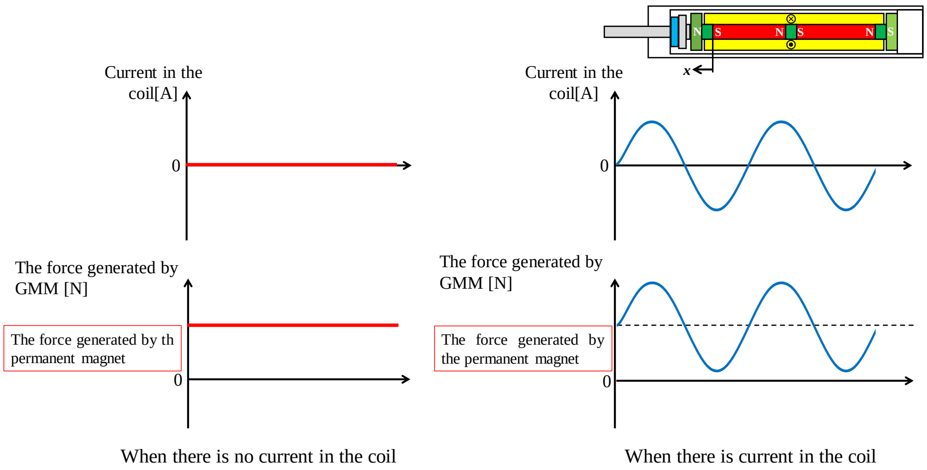


Fig. 8. Relationship between a current flow through the solenoid coil and magnetostriction force

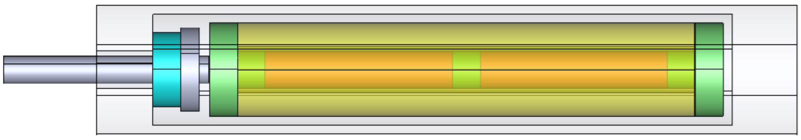


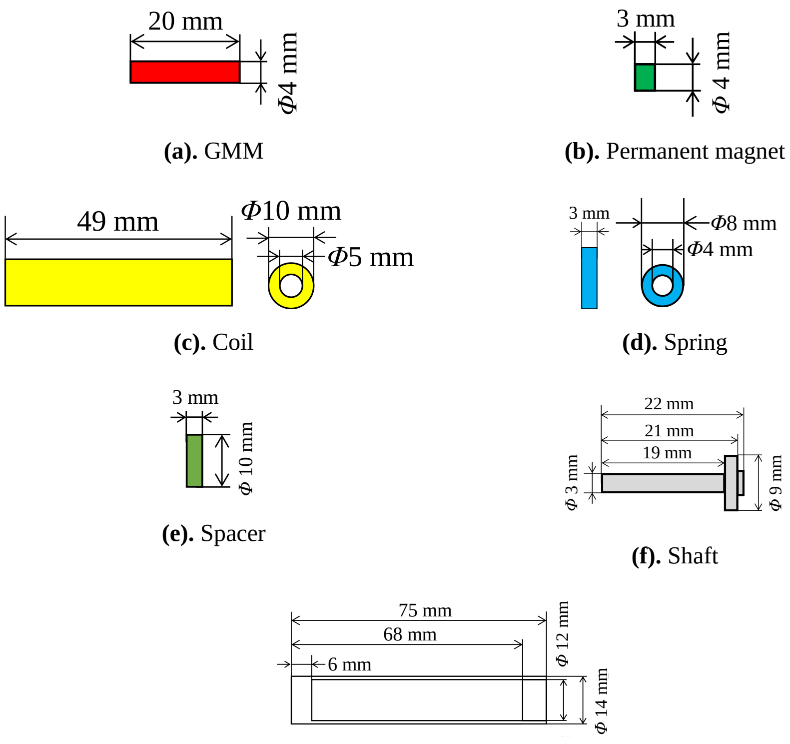
Fig. 9. FEM of GMA

5 Analytical study on magnetostriction force of the GMA

5.1 FEM model

In this study, we considered the output performance of the GMA which is used as an actuator for the acoustic control system of the ultracompact EV using the finite element model (FEM). Fig. 9 shows the model of FEM and Fig. 10 shows the size, internal structure, and each component of existing the GMA for the electromagnetic field analysis. Moreover, Table 2 shows the material of each component.

For the FEM, two Terfenol-D with a length of 20 mm and a diameter of 4 mm were arranged in series. Samarium cobalt magnets with a length of 3 mm and a diameter of 4 mm were



(a). GMM **(b).** Permanent magnet **(c).** Coil **(d).** Spring **(e).** Spacer **(f).** Shaft **(g).** Outer case

Fig. 10. Dimensions of each part of the GMA

Table 2. Details of the material of each component.

Components	Material	Electrical resistivity
Permanent magnet	Samarium-cobalt magnet	0.9×10^{-4}
Shaft / Spring / Spacer / Outer case	S45C	1.8×10-5
GMM	Terfenol-D	6.0×10^{-7}

placed between the two GMMs and at both ends. The permanent magnet was magnetized in the axial direction to be applied in the axial direction of the GMM.

In this analysis, the material characteristics of GMM were used as the value of the magnetic field and magnetic flux density as shown in fig. 11 and the result of size change by the external magnetic field of GMM as shown fig. 12 [20]-[21]. The young's modulus of GMM is 26.5 GPa. In this consideration, we carried out a three-dimensional analysis. The number of divided elements was 29653 and the number of nodes was 5570.

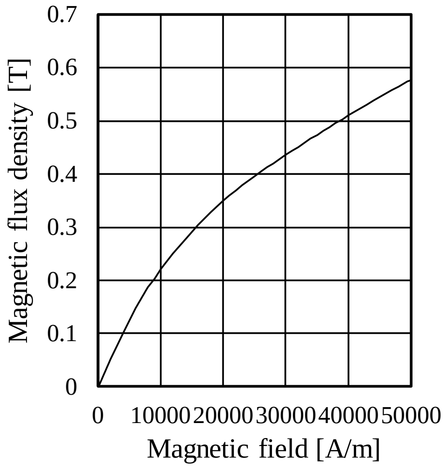


Fig. 11. B–H curve of the GMM.

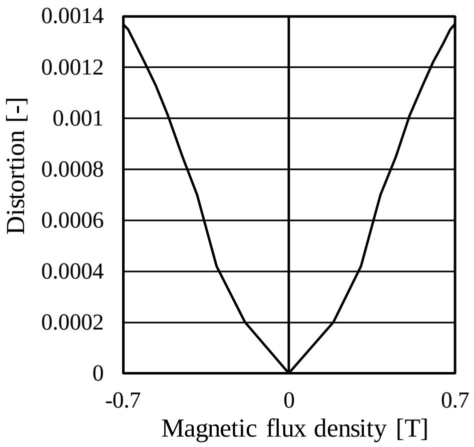
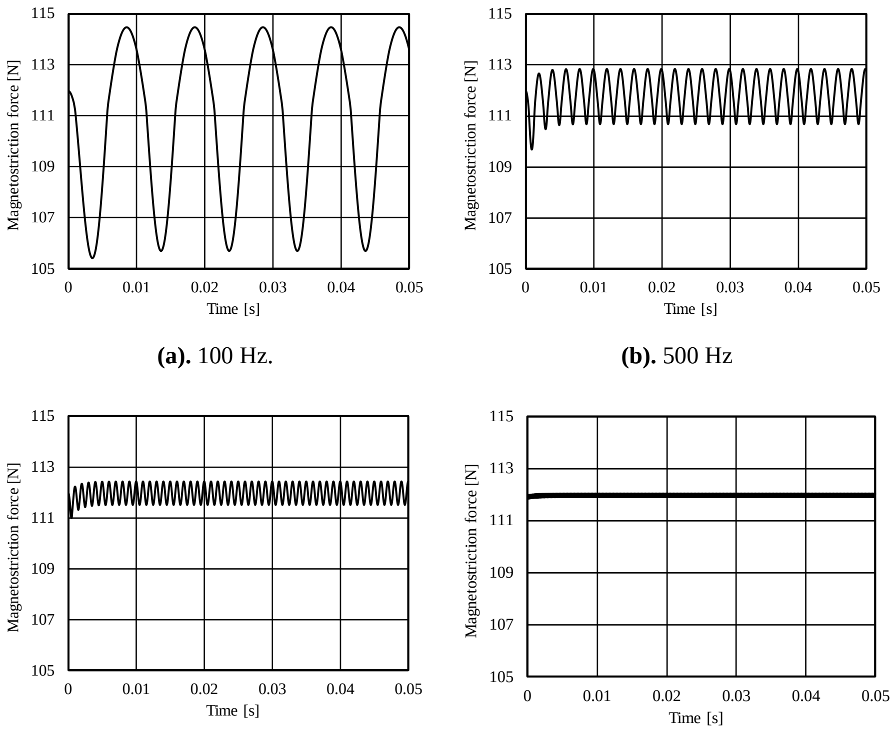


Fig. 12. B–H curve of the GMM.

5.2 Comparison of the magnetostriction force by changing the frequency of the AC source considering the use of piezoelectrically controlled amplifiers.

In the proposed interior acoustic control system, we are supposed to use piezoelectrically controlled amplifiers when installing a GMA in the wall of the ultracompact EV and output sound. When we used piezoelectrically controlled amplifiers, the actuator inductance affects output performance. Therefore, we conducted an analytical consideration of the magnetostriction force for low to high-frequency ranges. We analyzed magnetostriction force and magnetic flux density when the AC voltage was changed the frequency applied to the coil from 100Hz to 5000Hz. In this analysis, the sampling frequency was 20 kHz



(a). 100 Hz.

(b). 500 Hz

(c). 1000 Hz

(d). 5000 Hz

Fig. 13. Magnetostriction force time histories.

and the voltage amplitude was 1 V. In the establishment of electromagnetic field analysis, the analysis time increment was 50 μs, the step number was 1000 and the shaft and GMM were considered eddy current.

Fig. 13 shows the time history of the magnetostriction force of the entire contact surface between GMM and shaft. Fig. 13(a) is 100 Hz, (b) is 500 Hz, (c) is 1000 Hz, (d) is 5000 Hz. From the results, the amplitude decreased according to increasing frequency. And Distortion occurred in the waveform at 100 Hz. Current designs distort frequencies as low as 100Hz. Therefore, we will improve this problem by lengthening the shape and increasing the diameter of the GMM in the future.

Fig. 14 shows both amplitude values of the magnetostriction force at each frequency. The magnetostriction force decreased from 9 to 3 N in the 100 to 500 Hz which is road noise frequency range targeted by ANC. Furthermore, the magnetostriction force of 5000 Hz is 0.2 Hz. Therefore, it was found that the frequency was reduced to approximately 1/45 compared to 100 Hz. From the results, when we used the GMA for the proposed interior acoustic control system, the GMA had sufficient output performance of control sound wave by ANC for low-frequency noise such as road noise from 100 to 500 Hz.

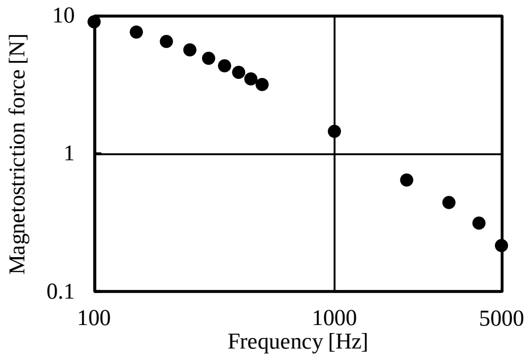


Fig. 14. Amplitude values of the magnetostriction force at each frequency.

6 Conclusion

In this paper, we conducted a basic study to design the GMA applying the proposed Interior acoustic control system which we analytically investigated the characteristics of the magnetostriction force when GMSs were deformed by a magnetic field using electromagnetic field analysis. In this analytical study, we conducted the magnetostriction force for changing frequency ranges of piezoelectrically controlled amplifiers using the FEM of the GMA. From the results, when we used the GMA for the proposed interior acoustic control system, the GMA had sufficient output performance of control sound wave by ANC for low-frequency noise such as road noise from 100 to 500 Hz. However, we need to consider changing the actuator's size, weight, shape, and components, as well as changing to a material with higher magnetic permeability to output a wider range of frequencies such as music.

In the future, we aim to create the GMA which is a higher magnetostriction force than the existing actuator. In addition, we conducted the installation position of the GMA and wall that can efficiently output sound waves by structural analysis and electromagnetic field analysis.

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