A barrel-stave projector with active material shell

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Abstract: A new barrel-stave transducer with special active shell made by giant magnetostrictive material Fe-Ga alloy called Galfenol is presented. Finite element analysis is carried out to simulate the magnetic fields and electroacoustic performance of them at first. It is shown that the projector with active shell could achieve better performance. Then two prototype transducers with the same volume and weight are fabricated and measured. The maximum transmitting current response is 168.4dB at the resonant frequency of 1750Hz for the one with Galfenol shell, and its maximum source level reaches to 180.1dB. In comparison, the maximum transmitting current response is 163.6dB at 1900Hz, and the maximum source level is 175.3dB for another with aluminum shell. It is confirmed that the barrel-stave transducer with active material shell has lower working frequency and higher sound power under the same conditions.

Key words: Galfenol; Barrel-stave; Flextensional transducer; Finite element analysis.

1. Introduction

The barrel-stave projector[1] which belongs to Class I flextensional transducer could combine low frequency and high power performance with a simple design to be lightweight, compact and low-cost. Consequentially, a lot of research work has been done on its working principle, design method and optimization technique[2-8]. Generally, it consists of a driving element, two end plates as the head and tail mass respectively and a shell coupling one end plate to the other. The expansion and contraction of the driver is transmitted to the shell and results in an enhanced volume velocity. The driving element could be made up of piezoelectric ceramic material, rare-earth giant magnetostrictive material[9] or the union of them[10].

In recent years, a new type rare-earth giant magnetostrictive material of Fe-Ga alloy called Galfenol[11-12] is becoming more and more attractive because of its competitive strain capabilities, mechanical robustness and high magnetic permeability. Galfenol is suitable for working under tension as well as compression. It could be readily machined using conventional machining techniques and formed into various geometries using standard metal working practices. All of

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these attributes make Galfenol a promising new material for transducer design. According to the fine features of Galfenol, a novel barrel-stave flextensional transducer with shell made by this active material is presented in this paper. The goal is to achieve better performance by the optimization design of both mechanical structure and magnetic circuit for barrel-stave transducer.

2. Design of transducer

The diagram of traditional barrel-stave transducer driven by rare-earth giant magnetostrictive material with inactive shell is shown in Fig. 1. Several permanent magnet pieces and one external coil are used to offer the static bias magnetic field and dynamic working magnetic field needed for the magnetostrictive driver respectively. Yoke components are necessary to shape the flux distribution and form a closed magnetic circuit together with the driving element including the magnetostrictive rods, magnets and spacers. And spacers placed between the driver and magnet pieces could help to make the magnetic field distribute more evenly. Both yokes and spacers are made by high magnetic permeability material such as electrical iron or silicon steel sheets. The head and tail mass should be made by nonmagnetic metal material such as steel and titanium alloy. And the inactive shell could be made by metal such as aluminum or polymer material such as carbon fiber.

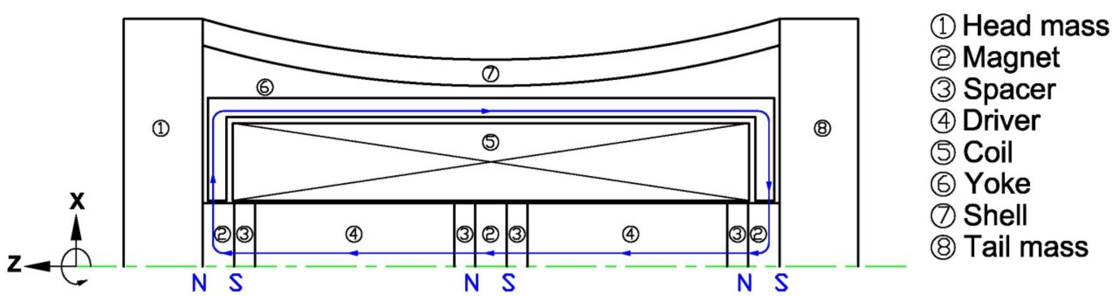


FIG. 1. The diagram of traditional magnetostrictive barrel-stave transducer with inactive shell.

The diagram of new barrel-stave transducer driven by magnetostrictive material with active shell made by Galfenol is shown in Fig. 2. It could be seen that some relatively structural modifications are required as follows. The yoke components would be removed. And the head and tail mass should be made by high magnetic permeability material at the same time. They would form the new external magnetic circuit together with the Galfenol shell for the driving element. The magnetostrictive driving material could be Terfenol-D or Galfenol in theory. Yet Galfenol driver should be the preferred choice generally because the shell is made by Galfenol and they are easy to get a good matching between each other in the magnetic circuit design.

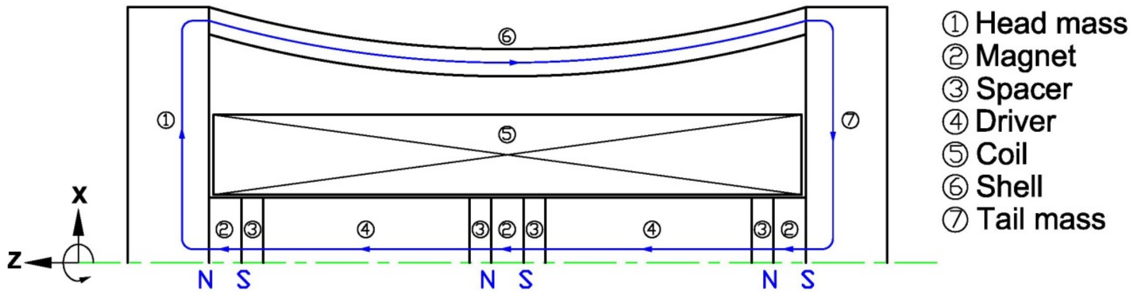


FIG. 2. The diagram of new magnetostrictive barrel-stave transducer with active shell.

3. Simulation results

3.1 Magnetic field analysis

For transducer driven by magnetostrictive material, it is necessary to do magnetic optimization analysis to increase the electroacoustical efficiency. Finite element analysis (FEA) has been used to complete the research. The magnetic FEA model for traditional barrel-stave transducer driven by Galfenol with inactive shell is shown in Fig. 3. The head mass, tail mass and shell of transducer could be ignored in this case because they are all made by nonmagnetic material.

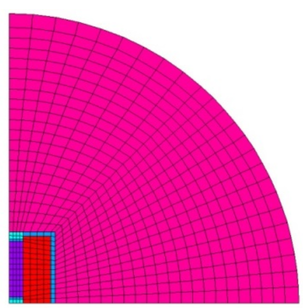


FIG. 3. The magnetic FEA model for barrel-stave transducer with inactive shell.

Because the magnetic strength B which is the feature parameter of magnetic analysis is proportional to the driving value, a normalized parameter Δ is needed to represent the uniformity of magnetic field. It is defined as

$$\Delta = (\mathrm{B_{max}} - \mathrm{B_{min}})/\mathrm{B_{max}} \times 100\%,$$

where $\mathrm{B_{max}}$ is the maximum value of magnetic strength, and $\mathrm{B_{min}}$ is the minimum value. Obviously, the magnetic field would be more uniform when Δ is smaller.

The simulated results of magnetic field in Galfenol rod for traditional barrel-stave transducer with inactive shell are shown in Fig. 4. The Galfenol rod used in the model has an outside diameter of 20mm and length of 40mm.

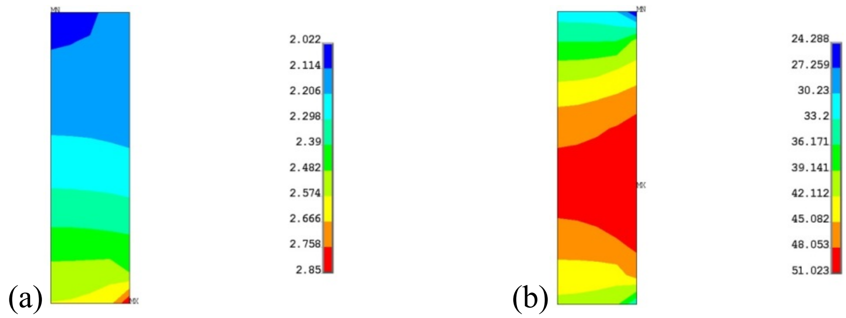


FIG. 4. The simulated results of magnetic field in Galfenol rod for barrel-stave transducer with inactive shell: (a) static magnetic field (b) dynamic magnetic field.

The magnetic FEA model for new barrel-stave transducer driven by Galfenol with active Galfenol shell is shown in Fig. 5. Now all the structural components including the head mass, tail mass and shell should be modeled and analyzed together because they are all important parts of the whole magnetic circuit.

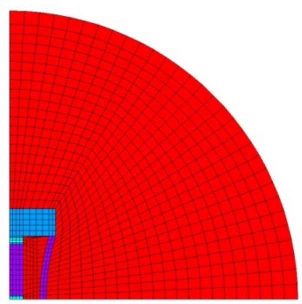


FIG. 5. The magnetic FEA model for barrel-stave transducer with Galfenol shell.

The simulated results of magnetic field in Galfenol rod for new barrel-stave transducer with Galfenol shell are shown in Fig. 6. The structural and magnetic parameters used in the analysis are the same as those for the traditional one.

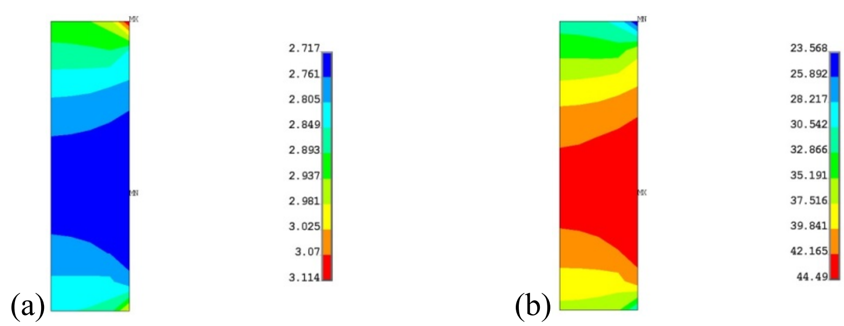


FIG. 6. The simulated results of magnetic field in Galfenol rod for barrel-stave transducer with Galfenol shell: (a) static magnetic field (b) dynamic magnetic field.

For the convenience of comparison, the simulation results of magnetic analysis above are collected in Table 1. To avoid the edge effect, the data of the central position in Galfenol rod is also listed out. It is recommended in the calculation of Δ because it could show the actual working state of Galfenol material better. It could be found that the distribution of magnetic field is more uniform in the driver of transducer with active Galfenol shell under the same driving condition which would help to make use of magnetic energy more efficiently.

Table 1. Comparison of simulated magnetic field results in Galfenol rod for barrel-stave transducers with active and inactive shell.

Δ(%)	Whole Galfenol rod		Central of Galfenol rod	
	Static magnetic field	Dynamic magnetic field	Static magnetic field	Dynamic magnetic field
Galfenol shell	12.7	47.0	6.2	26.1
Inactive shell	29.1	52.4	21.5	35.5

The simulated results of magnetic field in Galfenol shell for new barrel-stave transducer are shown in Fig. 7. The magnetic field strength in the shell is about one third of that in the rod according to detailed analysis. That means the maximum strain of shell would be about one third of the driving rod while the Galfenol material is working at its linear region. Because the volume of shell is much larger than the rod, the total volume displacement would increase a lot due to the contribution of active shell. Thus it could do favor to make the transducer has an enhanced sound radiation ability.

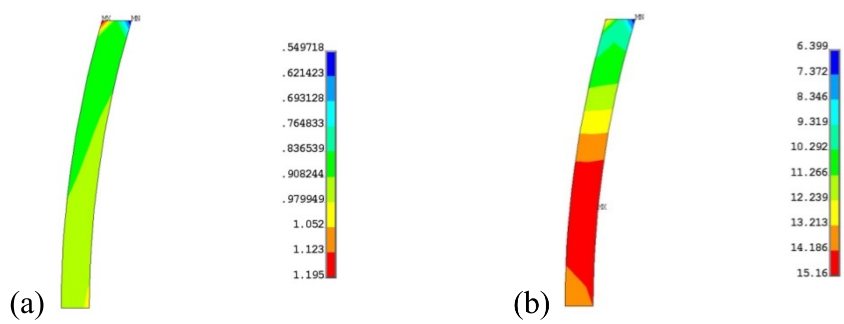


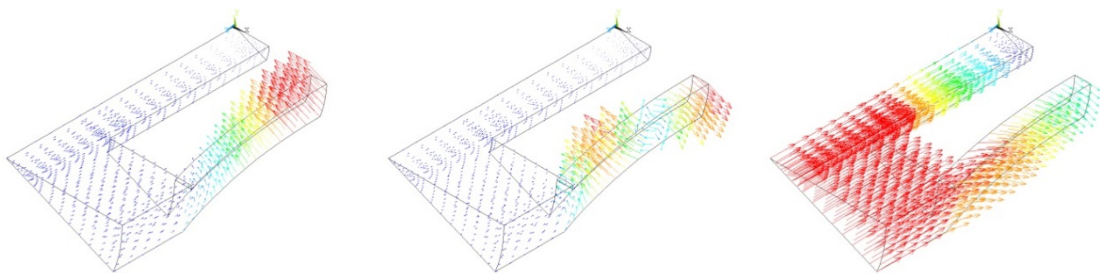
FIG. 7. The simulated results of magnetic field in Galfenol shell for barrel-stave transducer with Galfenol shell: (a) static magnetic field (b) dynamic magnetic field.

In summary, the barrel-stave transducer could have advantages of lower working frequency and higher sound power under the same conditions by using of an active shell in theory.

3.2 Modal analysis

The 3D FEA models of barrel-stave transducers with active and inactive shell for modal analysis could be built by software package ANSYS. The dimensions of them are the same with a maximum outside diameter of 67mm and length of 132mm.

The simulation results of modal analysis for barrel-stave transducer are shown in Fig. 8. They are the first two flexural modes and the hybrid of first flexural mode and longitudinal mode. Only the first flexural mode is suitable for high power applications because the whole vibration keeps in-phase with large amplitude.



(a) First flexural mode (b) Second flexural mode (c) Hybrid mode

FIG. 8. Main modes of barrel-stave transducer.

All the related frequencies of these modes for different materials are calculated as shown in Table 2. It could be seen that the resonant frequency of every mode for transducer with Galfenol shell is lower than that with inactive metal shell.

Table 2. Modal analysis results for barrel-stave transducers with active and inactive shell.

Modes	Galfenol shell	Aluminum shell	Titanium shell	Steel shell
First flexural mode	2945 Hz	3442 Hz	3632 Hz	3794 Hz
Second flexural mode	8415 Hz	12189 Hz	14495 Hz	14803 Hz
Hybrid mode	7034 Hz	8556 Hz	9606 Hz	10986 Hz

3.3 Transmitting current response

The transmitting current response (TCR) could be optimized by FEA harmonic analysis. The simulated TCR results of barrel-stave transducers with Galfenol and aluminum shell are both shown in Fig. 9. It could be seen that the maximum TCR is 168.2dB at the resonant frequency of about 1750Hz for the transducer with Galfenol shell, and the maximum TCR is 164.0dB at the resonant frequency of about 1950Hz for the transducer with aluminum shell. The new type projector could achieve better performance including lower frequency and higher sound power.

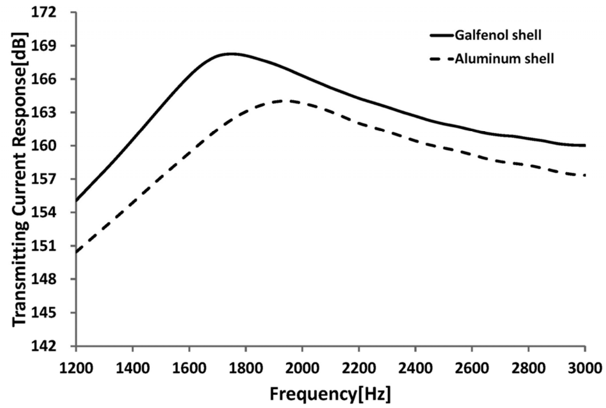


FIG. 9. The simulated results of transmitting current response.

4. Experimental results

On the basis of work above, the structural parameters of barrel-stave transducer could be determined. The prototype transducers are shown in Fig. 10. The dimensions of them are the same with a maximum outside diameter of 77mm and length of 155mm, and the weight are both about 2.5kg in air.

FIG. 10. The prototype barrel-stave transducers with Galfenol shell and aluminum shell.

The measured TCR results of prototype transducers are shown in Fig. 11. It could be seen that the measured results are in good agreement with the simulated predictions. The maximum TCR is 168.4dB at the resonant frequency of about 1750Hz for the transducer with Galfenol shell, and the maximum TCR is 163.6dB at the resonant frequency of about 1900Hz for the transducer with aluminum shell.

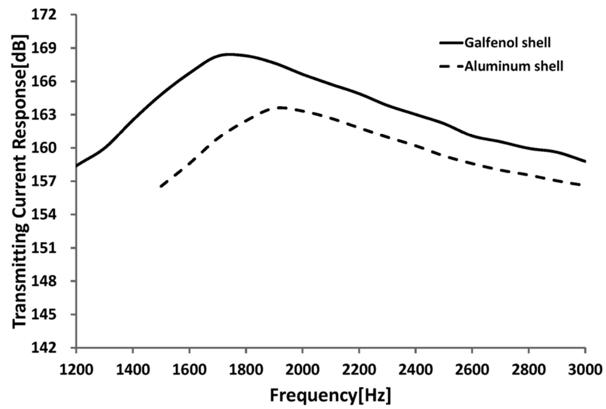


FIG. 11. The measured results of transmitting current response.

The measured results of source level (SL) are shown in Table 3. The maximum source level for the transducer with Galfenol shell reaches to 180.1dB at 1800Hz. In comparison, the maximum SL is 175.3dB at 1900Hz for the one with aluminum shell.

Table 3. The measured source level results of prototype barrel-stave transducers.

SL of transducers	1600 Hz	1800 Hz	1900 Hz	2000 Hz	2500 Hz	3000 Hz
Galfenol shell	178.8 dB	180.1 dB	/	177.3 dB	173.1 dB	171.2 dB
Aluminum shell	171.9 dB	/	175.3 dB	175.1 dB	171.8 dB	170.7 dB

In summary, the new transducer with active Galfenol shell could achieve better performance within the same dimension and weight.

5. Conclusions

A new type barrel-stave projector with special active shell made by giant magnetostrictive material Galfenol is introduced. It is proved that this transducer has lower resonant frequency and higher sound power under the same dimension and weight conditions by both the theoretical analysis and experimental results. Yet the operation theory is still hard to be applied to very low frequency transducer design at present due to the limited dimension of Galfenol material. Before the breakthrough in Galfenol processing technology, this problem could be solved by merging small components made by Galfenol into a large enough shell needed. Thus it is necessary to carry out research on solving the consequent problems such as the consistency of material, reliability of joint and so on. The ultimate goal is to make it more competitive over wider frequency range.

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