Finite Element Model Verification Magnetostrictive Terfenol-D Transducer

Lei An [a], Guozhu Zhao [b]
Civil Aviation Flight University of China, Guanghan 618300, China.
[a]anlei7@sina.com, [b]jude.1909@163.com

Abstract. Magnetic mass scaling Terfenol-D rods are preloaded bolt stress, permanent magnet biased magnetic field, the magnetic mass scaling Terfenol-D rods on the radial magnetic field, when to excitation coil pass excitation current, inside the coil is produced along with the changing magnetic field, current in the magnetic field Terfenol-D bar can produce movement, to promote sound plate.

Keywords: Terfenol -D, Magnetic mass scaling, biased magnetic field, radial magnetic field.

1. Introduction

The above designs are all based on piezoelectric materials, while GMM is a kind of high-technology functional material emerging in recent years after rare earth permanent magnet material and rare earth high-temperature superconductor material due to its excellent acoustic performance, which has a strong application in remote sonar and some underwater acoustic systems. This material is also a kind of material for designing conventional transducers, and there are already transducers developed with this material on the market.

Magnetostriction, as the name suggests, is when a material encounters a magnetic field. To be specific, the material is magnetized in the magnetic field, and the elongation or shortening effect will occur in the direction of magnetization when it is acted on by electrical signals. Ordinary magnetostrictive materials have been unable to produce high-power ultrasonic transducers due to their small strain and difficulty in coupling, which makes it impossible to realize large-scale application. In recent years, people are exploring a new kind of magnetostrictive material, which has high electromechanical conversion efficiency and can be used to design high-power transducers. This material is called supermagnetostrictive material.

The magnetostrictive coefficient "lambda" is normally used to indicate the size of the magnetostrictive effect, which is a very small unit representing one millionth of a metre. The magnetic strain of traditional magnetostrictive materials is very small, which limits its application prospect. The new super magnetic telescopic material is large - or more than two orders of magnitude larger than the conventional material. This is an amazing breakthrough from the 10-100ppm of traditional materials to the 1000-2500ppm. The magnetostrictive effect is shown in figure 1 below. [2, 3, 4].

2. Resonance Frequency

The energy is transferred in form of electromagnetic wave, the magnetostrictive value, electromechanical coupling factor, energy density and other parameters of supermagnetostrictive materials are much larger than those of traditional magnetostrictive materials [4,5,6]. This greatly broadens the field of practical application. It can be used in sonar systems, high-power ultrasound devices, ultrasonic flaw detection systems, precision control systems, high-energy micro-power sources and various sensors. It is also an ideal material for making directional acoustic transducers. This kind of magnetostrictive material has incomparable advantages of piezoelectric ceramic materials, especially suitable for high-power applications. It has high mechanical strength; high power will not cause damage to the system; Supermagnetostrictive materials do not have the problem that the residual polarization generated by a certain electric field in the manufacturing of piezoelectric ceramics will degenerate over time and eventually lead to polarization.

For high-power piezoelectric transducers, the piezoelectric materials may produce permanent depolarization. In this case, even the instantaneous overload may make the depolarization phenomenon more obvious, and even when the magnetostrictive materials are heated to the Curie point above, they will not produce those adverse reactions of piezoelectricity, but only instantaneous expansion. When the temperature drops, it can be recovered, indicating that the material's performance is very stable and reliable. Since the mid-1970s, the focus of GMM research has been on the preparation process of materials and the influence of each material component on their properties, which has accelerated their practicality and productization. Around the 1990s, some countries realized industrialized GMM production, such as terfenol-d of Etrema company in the United States and Magmek86 of a company in Sweden. Subsequently, the TbDyFe2 type GMM rod was developed in Britain, Japan, Russia and other countries including China, as shown in figure 2.

Began to engaged in the research of the material in the 90 s in China, there are a number of units and enterprises production GMM rod, such as gansu province gansu star rare earth functional materials co., LTD., baotou rare earth research institute, Beijing nonferrous metal research institute, institute of Chinese academy of sciences, pepper light rare earth material co., LTD., its main performance index and the approaching or has reached the international advanced level of similar products[8].

Table 1compares the physical properties of terfenol-d, Ni and PZT piezoelectric materials. As can be seen from the table, terfenol-d has obvious overall advantages over the other two materials. Terfenol-d has many advantages as shown in table 6, but its disadvantages are also fatal, and high cost is its biggest disadvantage. The material's price in the market are selling for the unit, and rare earth preparation tools and related research tool price is more expensive, scientific research cost is higher, led to many researchers gave up the research and also because of this, this article only to the design of the transducer with kinds of materials do the simulation without actual developing or buying. In addition, rare earth ultramagnetic terfenol-d also has the following disadvantages: 1. Relatively low permeability, easy to produce magnetic leakage; 2. Under the action of alternating magnetic field, high eddy current loss leads to poor high-frequency characteristics.3. Material is hard, brittle and fragile, mechanical processing difficult, low tensile strength cannot withstand the greater pull [9].

3. Schematic Electric Circuit Drawing of Inductive Coupling

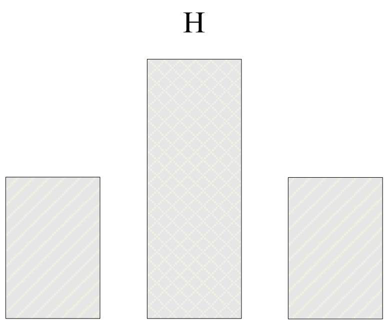


Fig. 1 schematic diagram of magnetostrictive effect

Fig. 2 terfenol-d products

Under the above conditions, parallel resonant can occur, at last reach wireless electric power transmission based on resonance. Figure 2 shows electric circuit model, after an electrical inductance L_2 and a capacitance C_2 are resonant, the resonant between L_2 C_2 and source will occur. The resonant frequency is given .This formula is used to solve frequency matching problem. As a result, the electric power consumed in the parasitic impedances is very little and can be negligible. In this electric circuit, a serial electric circuit is designed and parallel electric circuit will be studied in the later. To find the value of the capacitor, let L_1=30.9μH. The Figure1 can be modeled at f =1kHz~30kHz. The figure above gives L_2=1.2μH. L_1 and L_2 are the values of primary Tesla coil and secondary Tesla coil. The two Tesla coils are made of electrically conducting wire and they are approximately same. The distance between L_1 and L_2 is labeled D[10]. FIG. 3 is a schematic diagram of the structural principle of a cylindrical magnetostrictive transducer designed, which is mainly composed of sound plate 8, prestressed spring 3, magnetostrictive terfenol-d rod 7, shell 9 and excitation coil 4.

Basic working principle is: magnetic mass scaling Terfenol - D bar 7 are preloaded bolt stress, permanent magnet 5 produce bias magnetic field, the magnetic mass scaling Terfenol - D bar 7 on the radial magnetic field, when the excitation coil 4 pass on exciting current, inside the coil is produced along with the changing magnetic field, current in the magnetic field Terfenol - D bar 7 can produce movement, to promote sound board eight vibrations, isothermal, realization of energy conversion, each work, magnetic mass scaling Terfenol - D rods are spring 3 bounce back. The main role of spring 3 between the magnetostrictive terfenol-d rod and the radiant plate is to bear and adjust the prestress applied on the magnetostrictive terfenol-d rod and provide the displacement space for the radiant plate 8.

Table 1. comparison of physical properties of terfenol-d, Ni and PZT piezoelectric materials

	Items	PZT	Ni	Terfenol-D
elasticity	Saturated	100-600	-35-40	1500-2000
	The	0.65-1.0	0.03	14-25
	Dynamic	0.3	-	1.7
	Mechanical	0.45-0.72	0.30	0.7-0.75
	Energy	23-52	9	49-56
	The	≈10	-	<1
Acoustic danamics	Tensile	76	-	28
	The	-	-	700
	The	7.5	-	9.25
	Modulus	4.6-6	21	2.5-3.5
	The	130	4950	1720
	The	4	-	20
other	Coefficient	2.9	12.9	12
	The	1×10^{8}	-	6×10^{-7}
	Relative	-	-	3-15
	Curie	130-400	>500	380-387

The resonance frequency of *LC* electric circuit is *fs*. In theory, when *f* is close to or equals to *fs*, the oscillation of source resonance electric circuit is strongest, the value of resonance current is highest, and the magnetic field intensity H is also strongest. Inductor *L* and capacitor *C* is designed a receiving terminal resonance electric circuit to produce resonance depending on the magnetic field which generated by source terminal resonance electric circuit. The resonance frequency of receiving terminal electric circuit is *fs*, the parameters of *L* and *C* need not be in full accord with the source resonance electric circuit. What the receiving terminal resonance electric circuit must need is to ensure $ft = fs$. That is the necessary condition for energy Transmission.

In the work described here, there are two conclusions: This experiment demonstrates wireless electric power transmission with a *LC* resonant electric circuit; This experiment result shows that the resonant frequency is 18 kHz with *C*=100μF at distance *D*=3mm; another resonant frequency is 22 kHz with *C*=470μF at distance *D*=4mm. When the system works at the resonant frequency, R_L will receive the maximum electric power and$P_1=U^2max/R_L$=$3.1^2/6.9$ =1.4W, $\eta=P_1/P_2$=1.4W/3.3W=42%.

This electric circuit provides a simple method to achieve resonant coupling between source Tesla coil and receiving Tesla coil.

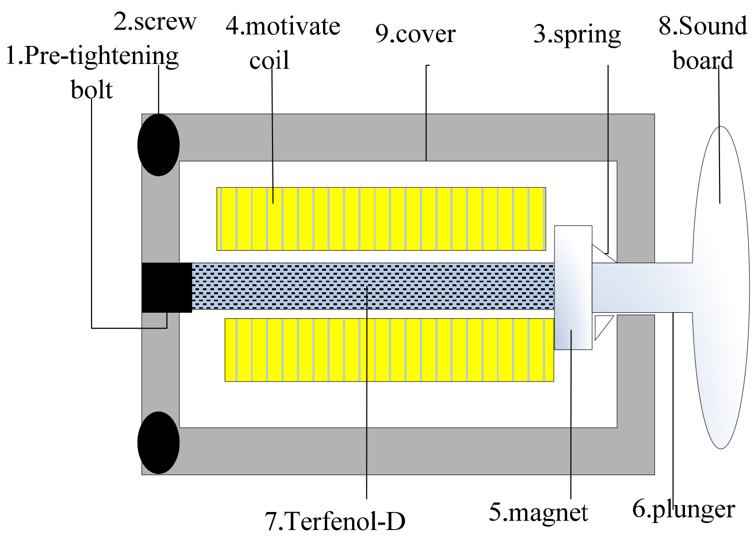


Fig. 3 structural schematic diagram of the magnetostrictive actuator

For the experimental setup with a load, the receiving terminal maximum voltage across a resistive bulb placed in the receiving terminal is 3.1V, corresponding to wireless electric power Transmission delivered electric power of 1.4W. When the receiver is displaced 10mm away from the axis of the transmitting Tesla coil, the voltage drops from 3.1V to 0.44V. In this electric circuit model, electric power disappears by means of electric power dissipation in the resistances. For these parameter values showed in the Figure4, much of the electric power leaves in the terminal of the source (electric power dissipation in the resistance R_S). 42% of the electric power is delivered to the load resistance R_L.

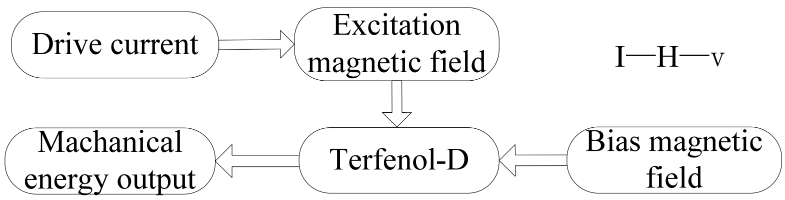
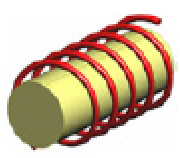
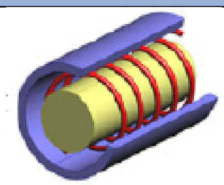
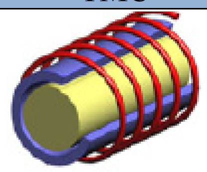
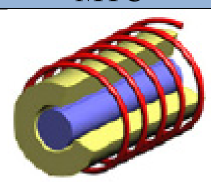


Fig.4 electrical-magnetic-mechanical energy conversion

Table 2. classical topologies of magnetostrictive transducers

Classic topology	TC	TCM	TMC	MTC
Magnet Terfenol-D Coil				
Offset field type	Dc coil	Dc coil	A permanent magnet	A permanent magnet
Magnetic field intensity	low	low	Medium and high	high
Terfenol - D shape	Stick or strip	Stick or strip	rod	The hollow rod
structure	simple	simple	medium	complex
Parasitic field	low	low	medium	high

It can be seen from Table 2that the classical structure topology of magnetostrictive transducer. Among them, TCM was selected as the research target, the main reason for which is that bias magnetic field is easy to be generated and designed. In particular, it is ok to add dc bias magnetic field outside the ac coil.The transient analysis type was adopted to define the boundary condition of the vector magnetic potential as follows: the magnetic flux was parallel to the boundary of the shell, and manual grid division was adopted, with an accuracy of 0.02. The following two tables 8 refer to various parameters of the design of all transducers.

Table 3. material parameters

parameter	value
Copper coils	$\mu_r=1$ $\mu_r=1$, $\rho=2.5\times10^{-8}\Omega\cdot m$
The relative permeability of air	$\mu_r=1$ $\mu_r=1$
Terfenol - D	$\mu_r=5$, $\rho=6.0\times10^{-7}\Omega\cdot m$
The relative permeability of a steel case	$\mu_r=1000$
The relative permeability of an elastic cover	$\mu_r=2000$
The relative permeability of the skeleton	$\mu_r=1$

In FIG. 5, FIG. A is the finite element model of magnetic field. as can be seen from the simulation images, terfenol-d has an obvious magnetic field distribution. In the interior of terfenol-d, the magnetic field is the strongest, while it weakens around it in turn.A good design for this transducer is to use a large sounding board to emit ultrasonic waves into the air.The verification of the magnetic stretching transducer will be involved in the subsequent research work. This paper will not conduct the test for technical and cost reasons.

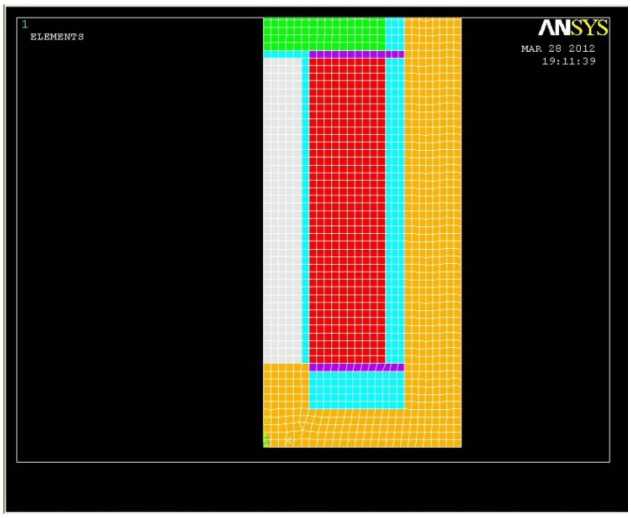


Fig. 5 finite element model of magnetic field

4. Efficiency of Electric Power Transmission

Under the stable working state of the transducer, the magnetostrictive terfenol-d rod will produce the telescopic effect. In this way, the sound wave is generated in the continuous vibration of the sound wave board. If the sound wave board is well coupled with the air, the sound wave can be "pushed" into the air. The sound board and the liquid medium coupling well, can "push" sound waves into the water, this is the principle of underwater acoustic transducer. Among them, the bias magnetic field is an important factor of energy conversion, and its main function is to eliminate the frequency doubling phenomenon and make the transducer work in the linear region of the "strain Vs magnetic field" curve. If the bias magnetic field is set properly, the energy conversion efficiency will be higher. Bias magnetic field can be used in a dc bias and permanent magnet bias, figure 3 is the permanent magnet biased, the design and use and dc bias is on the drive coil parallel dc signal, the ac-dc power sharing a coil, a magnetic bias agree with applying the alternating magnetic field of high and low, so we can guarantee the uniformity of bias magnetic field, which is the biggest advantage of this dc bias.

Permanent magnet biasing is the addition of permanent magnets at either end of the bar or in the middle. This advantage is simple structure, no need to add a dc power supply, reduce the circuit structure; The disadvantage is that the uniformity of the magnetic field is related to the position of the permanent magnet, and the uniformity of the magnetic field cannot be guaranteed, and the large current ac magnetic field may demagnetize the permanent magnet, as shown in FIG. 3.

The dc bias magnetic field in the transducer and the ac/dc magnetic field formed by the driving current together constitute the conversion of "electrical energy -- mechanical energy -- magnetic energy", as shown in FIG. 4. The constitutive relationship and mechanical properties of the magnetostrictive terfenol-d rod directly respond to the effectiveness of the design, and the bias magnetic field is an important factor to be considered.

Terfenol-d bar has different structural response rules from other materials, and the resonance frequency increases with the increase of bias magnetic field. In practical experiments, a constant magnetic field is generally generated by selecting a current. Generally speaking, setting a high bias magnetic field is more beneficial to the transducer designed to generate ultrasonic waves.

5. Summary

For an array composed of multiple power amplifiers, in order to make the array work synchronously, a series and parallel array is adopted. Generally, multiple power amplifiers are not needed to supply power to each transducer separately. The reason is that the design cost of multiple power amplifiers is relatively high, and the multiple power amplifiers cannot maintain the consistency of the signal when working alone. Because the failure of a single transducer may occur when multiple transducers are connected in series, the final design scheme is parallel transducer array.

By comparing the impedance curves obtained, it can be found that ordinary loudspeaker does not have resonant frequency, while the selected piezoelectric transducer has obvious resonant frequency. Through many tests and observations, it is found that its resonant frequency points are around 23kHz and 47kHz.However, due to the gap in design or production process, not all transducers are of this frequency, but are near these two frequencies. However, through a large number of tests, it is found that the selected group of transducers has a good consistency.

Through comparison, the series inductance impedance matching circuit with good matching effect and simple circuit structure is selected as the final circuit. As the inductance of 1.02mh is not easy to obtain, the inductance of 1mH is finally selected as the selected element, and the transducer constitutes a series circuit. In the later experimental process, the actual test result is better.

It can be seen from the finite element model of magnetic field that terfenol-d has an obvious magnetic field distribution, and in terfenol-d, the magnetic field is the strongest. At a frequency of 10kHz, it is feasible to increase the sound diameter of magnetic telescopic transducer by means of a sound board and realize its sound directivity.

In the following chapters, the design of directional acoustic transducer circuit platform mainly USES piezoelectric transducer as the basic element, on which tests and verification are carried out. The verification of the magnetic telescopic transducer will be carried out in the follow-up research work. Due to technical and cost reasons, the test in this paper will not be carried out for the time being.

Acknowledgements

This work was financially supported by fund project of Civil Aviation Flight University of China (J2019-101) and (J2015-63). Helicopter multi mission flight training device development, civil aviation innovation and guidance fund projects major projects (MHRD20130108).

References

[1]. A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljacic, “Wireless electric power transmission via strongly coupled magnetic resonances,” Science, vol. 17, pp. 83–86, Jul. 6, 2007.

[2]. Vandevoorde G, Puers R. Wireless energy transmission for standalone systems: a comparison between low and high-power applicability. Sensors Actuators. 2001; A 92:305–11.

[3]. Benjamin L. Cannon. Inductive coupling As a Potential Method for Wireless Electric power Transmission to Multiple Small Receivers. IEEE Transactions on Electric power Electronics, July 2009, Vol. 24, 1819-1825.

[4]. Wang CS, Stielau OH, Covic GA. Load models and their application in the design of loosely coupled inductive power transmission systems. Proceeding of Power System Technology. 2000; l2:1053–8.

[5]. Ghahary A, Cho BH. Design of transcutaneous energy transmission system using a series resonant converter. IEEE Trans, Power Electron. 1992;7: 261–9.

[6]. A. Karalis, J. D. Joannopoulos, and M. Soljacic, “Efficient wireless nonradiative mid-range energy transmission,” Ann. Phys., vol. 23, no. 1, pp. 4–48, Jan. 2008. 14. Lenaerts B, Puers R. Inductive powering of a freely moving system. Sensors and Actuators. 2005:522–3.

[7]. Lenaerts B, Puers R. An inductive power link for a wireless endoscope. Biosensors and Bioelectronics. 2006; 6:1–6.

[8]. Theodoridis MP, Mollov SV. Distant Energy Transmission for Artificial Human Implants. IEEE Transactions on Biomedical Engineering. November 2005;52: 191–8.

[9]. W. C. Brown. The History of Electric power Transmission by Radio Waves. IEEE Trans. Microwave Theory Tech, 1984, Vol. 2, 1230-1242.

[10]. K. Finkenzeller, RFIDHandbook: Fundamentals and Applications in Contactless Smart Cards and Identification 2nd ed. New York: Wiley, 2003, Ch. 4.