Design and Optimization of Electromagnetic Ultrasonic Body Wave Probe Based on Halbach Structure

*ZHANG Maiyi**, *CHEN Renwen*, *ZHANG Yufeng*

College of Aerospace Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, P.R.China

(Received 26 April 2022; revised 18 July 2022; accepted 7 August 2022)

Abstract: A shear wave electromagnetic acoustic transducer (EMAT) optimized structure is proposed by using circumferential annular Halbach magnet structure. Based on the orthogonal test, the effects of the coil conductor width, the spacing between adjacent conductors, the number of turns and the lifting distance on EMAT energy conversion effect are studied, and the optimal parameter combination is given. The structural design of the Halbach magnet is proposed. The cost coefficient S of the Halbach structure is defined, and the optimal thickness of auxiliary magnetic pole is obtained. The optimized EMAT coil diameter is reduced by 35% and the echo signal strength is significantly improved. Finally, C-scan imaging is carried out on the sample to verify the detection ability of EMAT.

Key words: debonding; electromagnetic ultrasound; optimum design; Halbach

CLC number: TB552 **Document code:** A **Article ID:** 1005-1120(2022)S-0127-08

0 Introduction

Metal / nonmetal bonding structures are widely used in aerospace, national defense and other fields. As a common process means, bonding has the advantages of simple operation, excellent damping performance and uniform distribution of connection stress. On the other hand, unavoidable defects such as debonding and weakening of bonding strength seriously affect the safety and service life of the structure[1]. It has important military and economic value for the evaluation of bonding quality. At present, a variety of nondestructive testing methods have been used to evaluate the bonding quality. Among them, ultrasonic testing method has attracted extensive attention because of its convenient use, high efficiency and intuition.

Compared with the traditional piezoelectric ultrasonic testing methods, electromagnetic ultrasonic testing technology has many advantages, such as non-contact, no coupling medium, easy to produce various ultrasonic waves[2-3], and even can be applied in special occasions such as high temperature and isolation layer. It has very high application value and application prospect. For the applications in the fields of metal thickness measurement and bonding structure detection, the most commonly used method is pulse reflection method: When ultrasonic waves propagate in a certain speed and direction in materials and encounter heterogeneous interfaces with different acoustic impedance (such as debonding defects or bonding interfaces of tested objects, etc.), reflection, refraction and waveform conversion will occur[4], and the defect attributes will be judged by extracting the characteristics of echo. In the selection of waveform, the ultrasonic volume wave that can propagate arbitrarily in the medium is the main application waveform. Compared with the longitudinal wave, the shear wave has shorter wavelength and higher detection resolution under the same excitation frequency. Therefore, the electromagnetic ultrasonic shear wave detection technology is used to detect the bonding of metal nonmetal bonding interface.

*Corresponding author, E-mail address: myzhang97@nuaa.edu.cn.

How to cite this article: ZHANG Maiyi, CHEN Renwen, ZHANG Yufeng. Design and optimization of electromagnetic ultrasonic body wave probe based on Halbach structure[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2022, 39(S): 127-134.

http://dx.doi.org/10.16356/j.1005-1120.2022.S.017

Because the electromagnetic ultrasonic transducer (EMAT) with different performance has a great impact on the detection results in practical application, the optimal design of EMAT probe is a research hotspot at present. In this study, an EMAT probe based on Halbach magnet structure is designed, and the magnet and coil parts are optimized respectively. The detection and imaging experiments of metal nonmetal bonding structure are carried out to verify the detection ability of EMAT probe under this design.

1 Technical Principle

EMAT mainly includes three structures: Magnet, coil and tested part. The magnet is used to provide static magnetic field, and the coil is used to input high-frequency alternating current to excite ultrasonic wave or receive ultrasonic echo signal. The properties of the tested part do not belong to the scope of EMAT structure optimization design, but it is required to have conductivity or ferromagnetism.

1.1 Energy exchange mechanism

Based on electromagnetic effect, electromagnetic ultrasonic energy transfer mechanism mainly includes Lorentz force mechanism, magnetostriction mechanism and magnetization force mechanism. For ferromagnetic materials, after years of research and experiments, scholars at home and abroad have concluded that in the vertical magnetic field, the Lorentz force mechanism plays an absolutely dominant role, while the proportion of magnetostriction mechanism will not exceed 5%, and the magnetization force mechanism can be ignored[5]. In the shear wave detection using vertical magnetic field, the energy conversion principle based on Lorentz force energy conversion mechanism is shown in Fig.1.

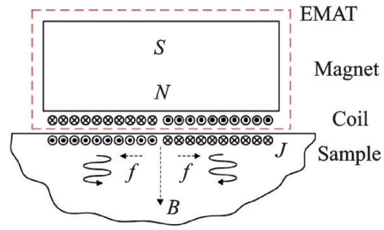


Fig.1 Energy exchange principle of Lorentz force mechanism

1.2 Principle of debonding detection

After the high-frequency alternating electric pulse is introduced into the coil, the induced eddy current J and alternating magnetic field will be generated in the skin depth of the tested part, and then the dynamic Lorentz force will be generated. The static Lorentz force is generated by the interaction of the external bias magnetic field and the induced eddy current J. Under the combined action of dynamic and static Lorentz forces, the particles in the tested part produce high-frequency periodic vibration and propagate in the form of waves. In the actual detection, the Lorentz force f generated by the static magnetic field B plays a leading role[6].

Fig.2 shows the electromagnetic ultrasonic testing method for interface debonding defects. In the detection of bonding state, when the ultrasonic wave propagates from the upper metal to the bonding interface, the reflectivity of the interface with good bonding quality is low, and most of the acoustic waves are transmitted. When the interface bonding quality is poor, most of the sound waves are reflected, and total reflection occurs in the case of debonding. The reception of reflected echo is the inverse process of excitation process. The general expression of echo signal received by EMAT coil is

$$U = kIn_1n_2B^2\rho Dh/z. \tag{1}$$

where I is the amplitude of the input signal, B the magnetic field strength, and z the acoustic impedance of the tested part; n_1 and n_2 are the turns of the excitation and receiving coil, respectively, and D and h the geometric size and lifting distance of the coil, respectively. According to the structural

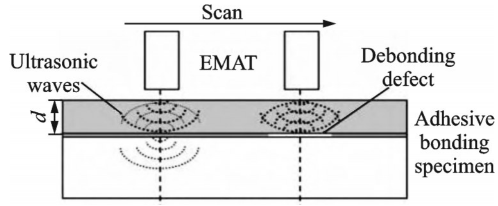


Fig.2 Electromagnetic ultrasonic testing method for interface debonding defects

characteristics of EMAT probe, the coil and magnet can be designed and optimized respectively.

1.3 Simulation model

The finite element model of steel / rubber bonded structure is established in the multi physical field simulation software COMSOL Multiphysics 5.3. In the experiment, the residual flux density of the uniform external bias magnetic field is set to be 1.4 T, and the direction is perpendicular to the surface of the tested piece downward. A sinusoidal pulse modulated voltage signal is connected to the coil, and its expression is

$$U = U_0 \times e^{-12e12 \times (t - t_0)^2} \cos\left(2\pi f (t - t_0)\right) \quad (2)$$

where U_0 = 500 V, time delay $t_0 = 6.67 \times 10^{-7}$ s, frequency f = 4.5 MHz. The line width is 15 mil (1 mil=0.025 4 mm), the conductor spacing is 8 mil, the number of turns is 15, and the lifting distance is 1.0 mm. Considering the skin effect, the number of grids in the skin layer on the steel surface shall not be less than 7. The simulation time is 5 000 ns. Fig.3 shows the displacement in the steel plate at 800 ns.

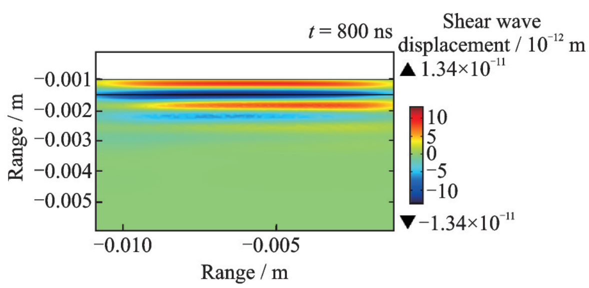


Fig.3 Propagation of ultrasonic wave in steel plate

2 Coil Design and Optimization

In order to excite the shear wave, the commonly used spiral coil is selected. Considering that there are many coil related design parameters, in order to reduce the number of experiments, the orthogonal test method is used to analyze the influence of various parameters on the excited ultrasonic intensity. Four parameters, such as line width (A), line spacing (B), number of turns (C) and lift distance (D), were selected to design a 4-factor 3-level orthogonal test[7]. The shear wave displacement peak W at the interface and the eddy current density P on the surface of the tested part are selected as the inspection indexes. The different levels of each factor are shown in Table 1. According to the experimental design, the $L_9(3^4)$ orthogonal table and experimental results shown in Table 2 are obtained.

Table 1 Factor levels of orthogonal test

Level	Factor			
	A/mil	B/mil	C	D/mm
1	10	6	13	0.8
2	15	8	15	1.0
3	20	10	15	1.0

Table 2 Orthogonal test parameter

EXP	Factor				Target	
	A/mil	B/mil	C	D/mm	W/ 10^{-11}m	P/ 10^9 (A•m^{-2})
1	10	6	13	0.8	**3.25**	**3.07**
2	10	8	15	1.0	2.18	2.33
3	10	10	17	1.2	**1.60**	**1.81**
4	15	6	15	1.2	1.86	2.09
5	15	8	17	0.8	2.09	2.34
6	15	10	13	1.0	2.45	2.69
7	20	6	17	1.0	1.85	2.08
8	20	8	13	1.2	2.09	2.40
9	20	10	15	0.8	2.36	2.63

According to the experimental results, the variation trend of shear wave amplitude and induced eddy current intensity in different levels of experiments is basically consistent, which is in line with the principle of Lorentz force mechanism. The parameter combination of EXP 1 with the largest shear wave amplitude is the current optimal parameter combination. At this time, the linewidth is 10 mil, the conductor spacing is 6 mil, the number of turns is 13, and the lifting distance is 0.8 mm. In fact, the experiment of four factors and three levels should have 81 parameter combinations, so it is necessary to further determine the optimal level in combination with range analysis. Taking the shear wave peak value W as the main inspection index, the results in Table 3 are obtained.

Taking the maximum amplitude of shear wave as the design objective, according to the analysis results, it can be seen that the optimal levels of line width, conductor spacing, turns and lifting distance are 10 mil, 6 mil, 13 turns and 0.8 mm respective-

Table 3 Range analysis results

Project		Factor			
		A/mil	B/mil	C	D/mm
Mean Valve	$\overline{k_1}$	2.34	2.31	2.60	2.57
	$\overline{k_2}$	2.13	2.12	2.13	2.16
	$\overline{k_3}$	2.10	2.14	1.85	1.85
Range	R	0.24	0.19	**0.75**	0.72

Note: $\overline{k_1}$, $\overline{k_2}$ and $\overline{k_3}$ are the mean values of the sum of different experimental results when the factor takes the corresponding level. R is the corresponding range.

ly. It can be determined that $A_1B_1C_1D_1$, i.e. EXP 1 parameter combination is the optimal parameter combination, and similarly, $A_3B_2C_3D_3$ is the worst parameter combination. Select $A_1B_1C_1D_1$ as the optimization result.

According to the range analysis, except for the conductor spacing, the other three factors show the characteristics that the smaller the horizontal value is, the higher the EMAT energy conversion efficiency is. The influence of wire turns and lift off distance on the experimental results is much greater than that of wire width and wire spacing. Even in this orthogonal test, the number of turns is the main influencing factor. However, in previous studies, people often pay attention to the influence of probe lift off distance and ignore the discussion of the number of turns. Compared with the parameter combination $A_2B_2C_2D_2$ before optimization, the shear wave displacement at the corresponding bonding interface of the coil with the three parameter combinations under the same magnetic field environment is shown in Fig.4. Fig.5 shows the physical comparison between the optimized coil and the original coil.

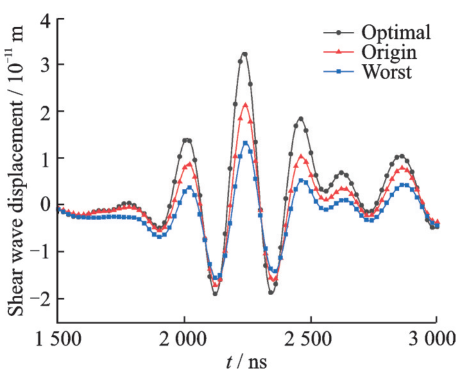


Fig.4 Shear waves excited by coils with different parameters

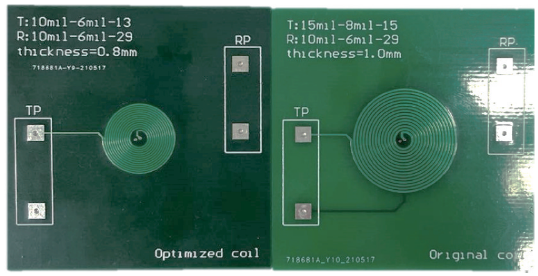


Fig.5 Coil before and after optimization

3 Magnet Design and Optimization

3.1 Halbach magnet structure

The optimization goal of the magnet part is to provide a stronger magnetic field pointing to the target detection area under the requirement of limited magnet size. Halbach magnet array enhances the magnetic field on one side and weakens the magnetic field on the other side by arranging a series of permanent magnets according to a certain law[8]. This characteristic just meets the requirements of electromagnetic ultrasonic technology for the direction of magnetic field. At present, the common Halbach structures are mainly linear, plane and cylindrical, which are mainly used in the fields of train braking, generator performance optimization and so on. Fig.6 shows the cross-sectional magnetic field distribution of a single group of linear Halbach magnet arrays.

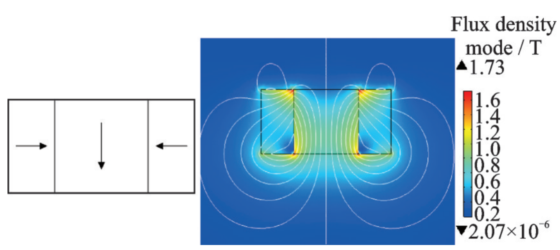


Fig.6 Single group linear Halbach magnet array

3.2 Optimization design of magnet structure

In the research on the enhancement of EMAT magnetic field intensity, Liu, et al. proposed a focusing structure[9], which can enhance the magnetic field intensity in the target range by focusing through the superposition of cylindrical magnets of different sizes. In order to compare the performance of ordinary cylindrical magnet, focusing structure and single group Halbach structure, under the conditions of equal magnet thickness, same material, same coverage area and same lifting distance, compare the induced magnetic field generated by the three structures on the surface of the tested part, as shown in Fig.7. Among them, the size parameters of the focusing structure are the parameters of article[9].

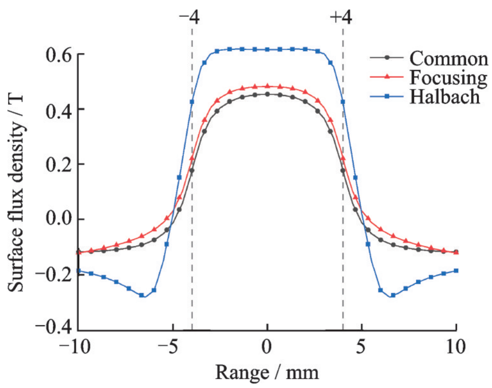
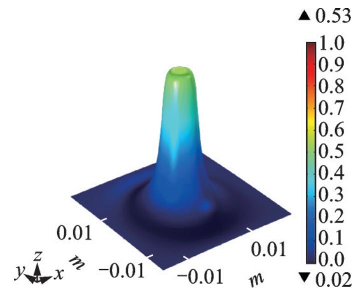
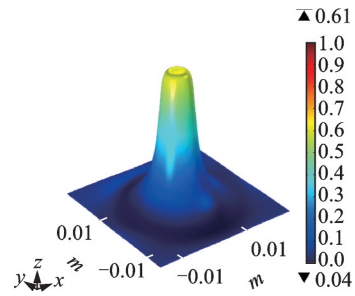
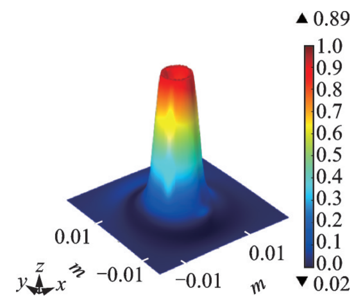


Fig.7 Magnetic field intensity distribution of magnets with different structures

Optimization design of magnet structure according to the results, Halbach structure can provide stronger magnetic field within the target coverage. Considering the structural characteristics of EMAT spiral coil, in order to make the magnetic field distribution in the whole coil coverage area conform to the circular characteristics, this study proposes to rotate the above single group of linear Halbach array around the center of the main magnetic pole for one cycle to obtain the circumferential Halbach structure magnet combination. The magnetic field distribution of the three structures in three-dimensional space is shown in Table 4.

Table 4 Magnetic field distribution of different structures

Structure	Flux density mode/T
 Common	
 Focusing	
 Halbach	

According to the simulation and comparison experiments, the circumferential Halbach structure proposed in this study can provide the strongest magnetic field strength among the three structures with equal thickness under the condition of the same target coverage. Compared with the structure of Liu et al.[9], the structure not only reduces the weight of the magnet part, but also improves the overall magnetic field strength. The regular shape is also convenient for fabrication and assembly.

According to the optimal coil parameters discussed above, the diameter of the main magnetic pole is 16 mm. The increase of the auxiliary pole width can significantly improve the magnetic field intensity on one side within the coverage of the main pole, but at the same time, it will lead to the significant increase of the magnet volume. In order to study the optimal value of auxiliary pole width, 8 groups of experiments were carried out, and the results are shown in Table 5. In order to discuss the relationship between the three and determine the optimal width of the auxiliary magnetic pole, a Halbach structure cost coefficient S is defined, which represents the maximum flux density mode increased by increasing the unit volume. In Eq.(3), T and V are the change values of the maximum flux density mode and volume of the two groups of data.

$$S=\frac{\Delta T}{\Delta V} \tag{3}$$

The curve of the cost coefficient S in Fig.8 is not monotonic and reaches the peak when the auxil-

Table 5 Auxiliary pole width selection experiments

Auxiliary pole width/mm	Maximum flux density mode/T	Volume/mm^3	S
3	1.01	28 900	
4	1.06	34 400	0.364
5	1.13	40 300	0.469
6	1.18	46 800	0.310
7	1.21	53 700	0.173
8	1.24	61 100	0.162
9	1.27	69 000	0.152
10	1.29	77 300	0.096

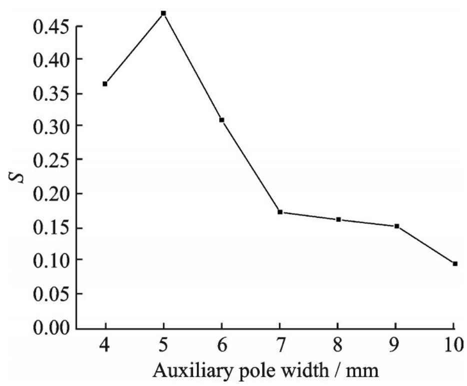


Fig.8 Halbach structure cost coefficient S curve

iary pole width is 5 mm. Before the width does not exceed 5 mm, the magnetic field intensity increased by the increase of unit volume is increasing. At this time, it is considered that the cost of the increase of width is positively acceptable; after exceeding 5 mm, the magnetic field strength increased by the increase of unit volume decreases continuously. At this time, it is considered that the cost of increasing volume is negative. Therefore, the width of the auxiliary pole is 5 mm.

4 Detection Experiment and Imaging

Table 6 lists the EMAT structural parameters before optimization. The diameter of the main magnetic pole is the value of the corresponding coil size plus 2 mm. Figs.9, 10 show the echo signals before and after optimization. Under the same conditions, the optimized EMAT echo amplitude is significantly improved, and the probe volume is reduced by 8%. The coil diameter is reduced by 35%, which correspondingly improves the resolution of EMAT probe. The optimized EMAT can stimulate higher

Table 6 EMAT structural parameters before and after optimization

Parameter	Size type	Origin value	Optimized value
Coil	Width/mil	15	10
	Spacing/mil	8	6
	Turns	15	13
Lift distance	Distence/mm	1.0	0.8
Main magnetic pole	Diameter/mm	22	16
	Height/mm	19	19
Auxiliary pole	Lenth/mm	/	5
	Width/mm	/	5
	Height/mm	/	19

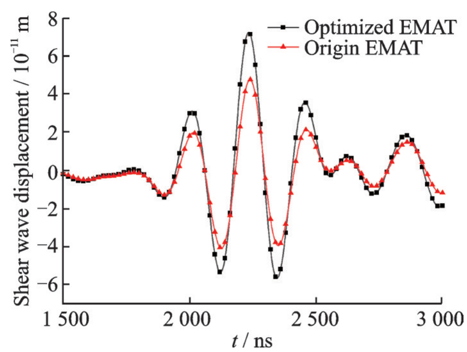


Fig.9 Simulation experiment of shear wave amplitude before and after optimization

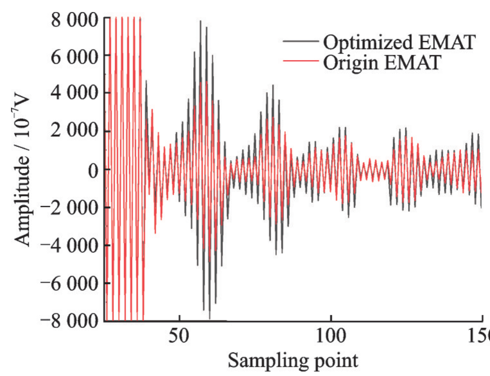
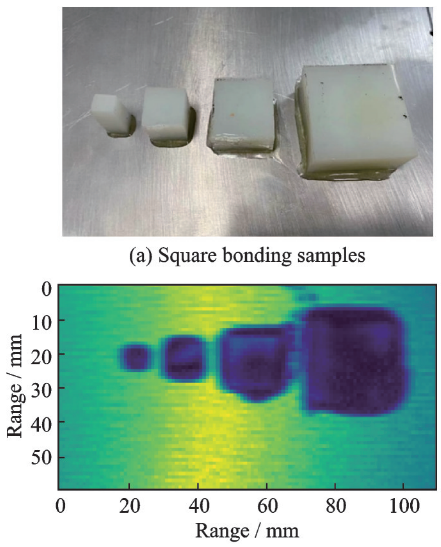


Fig.10 Echo signal before and after optimization in the experiment

intensity ultrasound, and then improve the intensity of echo signal.

In the iron / rubber partial square bonding sample shown in Fig. 11, the thickness of the bonding layer is 2 mm, and the widths of the well bonded test blocks are 1 cm, 2 cm, 3 cm and 5 cm, respectively. The four test blocks represent the positions with good bonding, and the periphery represents debonding. During C-scan, the scanning step is 2 mm. Due to the limitation of bonding process, glue overflows in varying degrees around the test block, and the test result is not a standard rectangular straight edge. The ultrasonic wave has attenuated a lot in the bonding layer, and the reflected echo is too few, so it is difficult to detect the debonding. The test results of the test block with a width of 1 cm are obviously sawtooth because the boundary is only 5 pixels, and the step can be reduced.



(a) Square bonding samples

(b) C-scan imaging of square bonding samples

Fig.11 C-scan experiment and imaging.

5 Conclusions

In summary, an electromagnetic ultrasonic body wave probe based on circumferential Halbach structure is proposed, that is, the magnet combination arranged according to a certain law is adopted in the magnet part to significantly enhance the magnetic field intensity on one side within the target range of the main magnetic pole. Based on the orthogonal test, the four parameters of wire width, wire spacing, coil turns and coil lifting distance are optimized, and the optimal parameter combination is obtained. After optimization, the coil diameter is reduced by 35%. According to the range analysis results, in addition to the lifting distance, the number of turns is also an important factor affecting the energy conversion efficiency. Referring to the structural characteristics of linear Halbach, the circumferential ring magnet is used as the auxiliary magnetic pole and the cylindrical magnet is used as the main magnetic pole. Under the same conditions, this structure can provide a stronger magnetic field in the target range than the structure in article[9]. The improved magnet structure is composed of a cylindrical magnet with a diameter of 16 mm and a height of 19 mm and an annular magnet with a width of 5 mm. The magnetization direction of the cylindrical magnet of the main magnetic pole is axial magnetization, and the magnetization direction of the annular magnet of the auxiliary magnetic pole is radial magnetization. The diameter of the main magnetic pole is determined by the coil, and the width of the auxiliary magnetic pole is determined by the proposed Halbach structure cost coefficient S. Experiments show that the optimized EMAT can significantly improve the amplitude of echo signal and reduce the volume of probe by 8%. Compared with the Halbach magnet structure proposed by Cai et al.[10], the effective magnet area ratio of this probe is significantly higher. Finally, the C-scan imaging of square bonding samples is carried out to verify the detection ability of the probe.

References

[1] DILEEP K, DAVID B, PRABHU R, et al. Detection of interfacial weakness in a lap-shear joint using shear horizontal guided waves[J]. NDT & E International, 2020, 112: 102248.

[2] FAN Xueteng, FU Xibin, HUANG Xuebin, et al. Total focusing imaging simulation and algorithm optimization of debonding defect of composite bonding structure[J]. Journal of Mechanical & Electrical Engineering, 2019(8): 791-796.

[3] DONG Jundong. Study on ultrasonic testing method Nanchang of metal-rubber multi-interface bonding quality[D]. Nanchang: Nanchang Hangkong University, 2019.

[4] ZHENG Shanpu, LU Minghui, WANG Jundong, et al. Ultrasonic testing method for debonding defects in multilayer structures[J]. Journal of Applied Acoustics, 2019(1): 134-141.

[5] RIBICHINI R, NAGY P B, OGI H. The impact of magnetostriction on the transduction of normal bias field EMATs[J]. NDT and E International, 2012 (51): 8-15.

[6] TANG Qin, SHI Wenze, LU Chao, et al. Optimization

design and experimental study of multi-layer spiral coils electromagnetic acoustic transducer[J]. Journal of Central South University (Science and Technology),2020(7): 1792-1803.

[7] XU Zhongan, WANG Tianbao, LI Changying, et al. Introduction to orthogonal experimental design method[J]. Science and Technology Information Development and Economy, 2019, 12(5) : 148-150.(in Chinese)

[8] QIN Jinchang, CHEN Renwen, ZHANG Yuxiang, et al. Virtual Halbach analytical method for improved Halbach magnetized PM slotless planar linear actuators[J]. International Journal of Applied Electromagnetics and Mechanics, 2020, 63(4): 583-599.

[9] LIU Tianhao, PEI Cuixiang, CHENG Xin, et al. Adhesive debonding inspection with a small EMAT in resonant mode[J]. NDT and E International, 2018, 98: 110-116.

[10] CAI Zhichao, LI Yibo. Optimum design of electromagnetic acoustic longitudinal wave transducer based on Halbach array[J]. Transactions of China Electrotechnical Society, 2021,36(21): 4408-4417.(in Chinese)

Author Ms. **ZHANG Maiyi** received her B.S. degree in traffic equipment and control engineering from Central South University of China in 2019. She is a postgraduate student in instrument science and technology in the State Key Laboratory of Mechanics and Mechanical Structure Control, School of Aerospace Engineering, Nanjing University of Aeronautics and Astronautics, China. Her research interests include mechanical fault diagnosis, nondestructive testing and signal processing.

Author contributions Ms. **ZHANG Maiyi** analyzed the problem, established the conceptual model of the algorithm and wrote the manuscript. Prof. **CHEN Renwen** designed and supervised the study. Ms. **ZHANG Yufeng** contributed to the discussion and background of this study. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor:CHEN Jun)

基于Halbach结构的电磁超声体波探头的设计与优化

张迈一,陈仁文,张雨枫

(南京航空航天大学航空学院,南京210016,中国)

摘要:提出了一种采用环形Halbach磁体结构的剪切波(Electromagnetic acoustic transducer,EMAT)优化设计结构。首先,基于正交试验,研究了线圈导体宽度、相邻导体间距、匝数和提升距离对EMAT能量转换效果的影响,并给出了最佳参数组合。然后,提出了Halbach磁体的结构设计,并定义了Halbach结构的成本系数S,得到了辅助磁极的最佳厚度。优化的EMAT线圈直径减少了35%,回波信号强度显著提高。最后,对样品进行了C扫描成像,以验证该EMAT的检测能力。

关键字:脱粘;电磁超声;优化设计;Halbach