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Optimal Design of Lamb Wave EMATs

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1. Introduction

Lamb wave electromagnetic acoustic transducers (EMATs) have been sucessfully utilized for on-line inspection of pipe lines and plates due to their advantages in noncontact, high-efficency and long-range detections[1]. However, the expansion of applications of Lamb wave EMATs are chiefly confined by two problems: (a) multi-modes and dispersion phenomena tend to cause difficulty in interpretation of echo signals and reduction of signal-to-noise ratio (SNR) and the spatial resolution[2]; (b) poor transduction efficiency of EMATs leads to low SNR of the inspection system[3]. Researchers have employed signal processing methods[2] and sophisticated transmitting and receiving circuits[3] to minimize the influence of above two problems, which inevitably increases costs and dimensions of the inspection system. To thoroughly solve these problems, we propose an optimal design method for Lamb wave EMATs by combining two-intersection-point method with orthogonal test method.

2. Method

Fig. 1 shows a typical Lamb wave EMAT operating on Lorentz principle, which consists of a magnet, a meander-line coil and an aluminum plate under test. In Fig. 1, l_1, w_1 are length and width of coil conductors, L is the spacing interval between neighboring conductors; l_2, w_2 and t_2 are length, width and thickness of the magnet, d is the plate thickness, and I_t is the excitation current. Assuming λ is the wavelength, L should be equal to 0.5λ to effectively excite Lamb waves with high directivity.

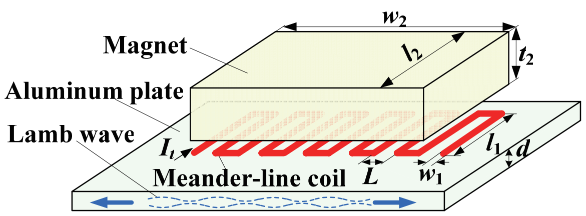


Fig. 1 Schematic diagram of Lamb wave EMATs

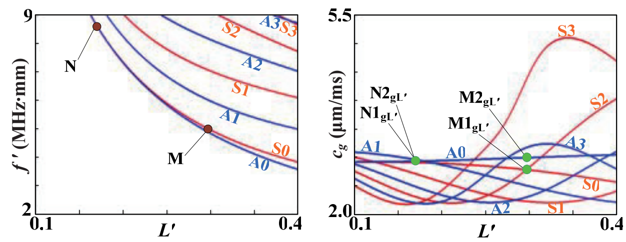
Combining the characteristic equations of Lamb waves with L=0.5λ shows that group velocities v_g and multi-modes and dispersion charateristic of the electromagnetic ultrasonic Lamb waves are determined by d, L and the frequecny f:

$$v_g = -2L'^2 \cdot \frac{\mathrm{d}f'}{\mathrm{d}L'} \qquad (1)$$

$$\frac{\tan\left[\frac{\pi}{2}\sqrt{\frac{4}{v_T^2}(f')^2-\frac{1}{(L')^2}}\right]}{\tan\left[\frac{\pi}{2}\sqrt{\frac{4}{v_L^2}(f')^2-\frac{1}{(L')^2}}\right]} = -\left\{\frac{\frac{1}{(L')^2}\sqrt{\left[\frac{4}{v_T^2}(f')^2-\frac{1}{(L')^2}\right]\left[\frac{4}{v_L^2}(f')^2-\frac{1}{(L')^2}\right]}}{\left[\frac{2}{v_T^2}(f')^2-\frac{1}{(L')^2}\right]^2}\right\}^{\pm 1} \qquad (2)$$

where v_T is velocity of shear waves; v_L is velocity of longitudinal waves; $f'=f/d$, and $L'=L/d$.

According to (1) and (2), L'-f' curves and L'-c_g curves are obtained, as shown in **Fig. 2**. The point (L', f') on L'-f' curves determines wave modes of Lamb wave EMATs, so it is defined as operating point. The slope at the corresponding point (L', c_g) on L'-c_g curves determines the dispersion of Lamb waves. In practice, the operating point is actually an operating zone due to the existence of the bandwidth of f and the variation of L.



(a) L'-f' curves (b) L'-c_g curves

Fig. 2 L'-f' curves and L'-c_g curves of Lamb wave EMATs

When the operating zone covers only one mode curve on the L'-f' curves, only the corresponding Lamb wave mode will be excited, which can directly avoid multi-modes phenonmeon.

However, when the operating zone covers manifold modes concurrently, multi-modes phenomenon emerges. In this case, we propose a "two-intersection-point" method to minimize the influence of multi-modes and dispersion phenomena, whose process is as follows:

(i) On L'-f' curves, finding an operating point (L_0', f_0') which is at the intersection point of mode curves, so that manifold modes of Lamb waves could be excited concurrently by an EMAT.

(ii) On L'-c_g curves, confirming the corresponding points (L_0', c_{g0}) of the exicted modes coincide with each other, that is these points are also at the intersection point of the mode curves. Thus, the concurrently excited modes of Lamb waves possess identical propagation velocities. They travel at the same velocity, which seems as if no multi-modes phenomenon emerges.

(iii) On L'-c_g curves, verifying if the slope of the mode curves at the corresponding points is zero.

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If it is zero, no dispersion appears; on the contrary, severe dispersion emerges, and a new operating point should be finded accroding to this process.

Using "two-intersection-point" method, the operating point of a commonly used Lamb wave EMAT for the inspection of a 10 mm thick aluminum plate is optimized based on equations (1) and (2). Before optimization, its operating point is M (0.293, 5); after optimization, the point is N (0.17, 8.62), as shown in Fig. 2 (a). Both of the points are in the vicinity of A0 and S0 mode curves, so A0 and S0 Lamb waves will be simultaneously excited. The corresponding points of M and N are $M1_{gL'}$, $M2_{gL'}$, $N1_{gL'}$ and $N2_{gL'}$, as shown in Fig. 2 (b).

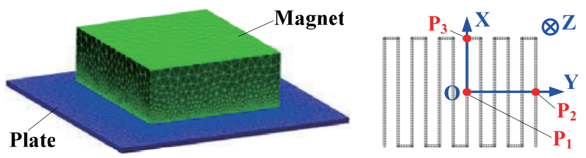
Parameters of the two operating points are compared in **Tab. I**, which indicates that before optimization, the group velocity difference between A0 and S0 mode Lamb waves is about 7.4%, while after optimization, the difference is only about 0.7%. Moreover, the absolute value of the slope of group velcity curve at N has decreased compared with that at M. Consequently, the influence of multi-modes and dispersion phenomena are minimized.

Tab. I Parameters comparison between operating points

Operating point	L (mm)	f (MHz)	Modes	c_g (mm/μs)	dc_g/dL'
M	2.930	0.500	S0	2.800	-1.7
			A0	3.008	0.5
N	1.700	0.862	S0	2.920	-0.4
			A0	2.940	0.3

After obtaining the optimal frequency f and spacing interval L, other EMAT parameters including l_1, w_1, d_1 (lift-off distance of the coil), l_2, w_2, t_2 and I_t are further optimized to enhance Lamb wave strength based on 3-D finite element analysis and orthogonal test method.

A 3-D finite elment model is established for the commonly used Lamb wave EMAT, as shown in **Fig. 3(a)**, where the coil is covered by the magnet. Cartesian coordinates are shown in **Fig. 3(b)**, where the origin O is on the plate surface.



(a) EMAT finite elment model (b) Typical positions

Fig. 3 EMAT finite element model and typical positions

Model parameters before optimization are: l_1 =35mm, w_1=1mm, d_1=0.5mm, l_2=40mm, w_2=40mm, t_2=15mm, I_t=100A, f=500kHz, L=2.93mm. Three typical positions P_1 (0, 0, 0), P_2 (0, 15.15, 0) and P_3 (17.5, 0, 0) on the plate surface under the coil are studied in Fig. 3(b). Simulation showed that when Lorentz force component in Y direction at P_1 and P_2 and Lorentz force at P_3 reach maximum, strongest Lamb waves would be excited[4].

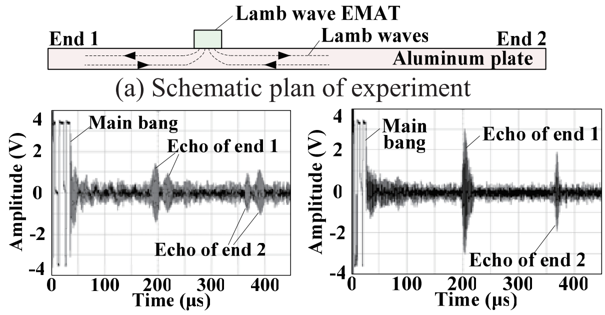
Orthogonal test method is employed to study the influence of parameters on the Lorentz force at P_1, P_2 and P_3. Variation ranges of the parameters are chosen according to frequency, transmitting power and working environment of EMATs. Each range of the parameter is divided into three levels, as shown in **Tab. II**. Orthogonal test is carried out using the orthogonal table $L_{18}(3^7)$ and eighteen different EMAT models are established according to Tab. II. Comparison and analysis show that d_1 and I_t have the greatest influence on the signal strength; w_1 and t_2 obviously affect the strength too; and the optimal parameters are: l_1=20mm, w_1=0.3mm, d_1=0.1mm, l_2=23mm, w_2=23mm, t_2=20mm and I_t=150A.

Tab. II Variation ranges of EMAT parameters

l_1 (mm)	w_1 (mm)	d_1 (mm)	l_2 (mm)	w_2 (mm)	t_2 (mm)	I_t (A)
17	0.3	0.1	20	20	10	50
20	0.6	0.5	23	23	15	100
23	0.9	0.9	26	26	20	150

3. Experiment

Experiment is done to compare EMAT's perfomance before and after optimization as shown in **Fig. 4**, which indicates that the multi-mode and dispersion phenomena has "disappeared" after optimization, and the signal amplitude of Lamb waves has increased by 216%.



(b) Before optimization (c) After optimization

Fig. 4 Echo signal comparison before and after optimization

4. Conclusions

An optimal design method combining two-intersection-point method with othogonal test method was proposed for Lamb wave EMATs. Experiment verified that, after optimization, not only the multi-mode and dispersion phenomena of Lamb waves were minimized, but also the signal amplitude had increased by 216%. As the signals became much clearer, stronger, and more energy-concentrated, practicability and applicablity of Lamb wave EMATs were greatly enhanced.

References

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