Lift-off Performance of Receiving EMAT Transducer Enhanced by Voltage Resonance

Xu DING 1, Hong BA 1, Xinjun WU 1, Lingsong HE 1

1 State Engineering Research Center of Manufacturing Equipment Digitization, Huazhong University of Science & Technology, Wuhan, 430074, P. R. China
Phone: +86 27 87559332, Fax +86 27 87559332; dingsugar@163.com, bahong198791@163.com, xinjunwu@mail.hust.edu.cn, helingsong@mail.hust.edu.cn

Abstract
Electromagnetic acoustic transducers (EMATs) are valuable non-contact ultrasonic transducers, which are suitable for high speed or high temperature inspection applications. When the lift-off, which is the distance between the EMAT coil and the sample surface, is increased, the coupling efficiency will dramatically decrease and the signal will be attenuated quickly. This paper proposes a method for enhancing the lift-off performance by voltage resonance. A voltage resonance circuit is constituted by the receiving coil and a capacitor. When the capacitance makes the resonant frequency equal to the ultrasonic frequency, the signal will be enhanced by the voltage resonance. The signals detected by the coil with capacitor and without capacitor in the lift-off range from 0mm to 6mm were obtained. Experimental results indicate that the amplitude is obviously enhanced and the attenuation rate due to the lift-off is decreased by the voltage resonance.

Keywords: electromagnetic acoustic transducer (EMAT), lift-off, voltage resonance

1. Introduction
Electromagnetic acoustic transducer (EMAT) is a valuable non-contact, electromagnetic coupled ultrasonic transducer. EMAT can be used to generate and detect ultrasound in electrically conducting or ferromagnetic samples without couplant, and is suitable for high speed or elevated temperature inspection [1-3]. However, the efficiency of EMAT is very low and is dependent on the lift-off, which is the distance between the EMAT coil and the samples surface. The received signal will be attenuated quickly with the increase of lift-off. If the lift-off is too large, the signal detected by EMAT will be too weak to be recognized. On the other hand, the variation of lift-off leads to sharp change of signal amplitude. It is a practical problem in application of EMATs automatic inspection system.

It has been reported that Lift-off performance of EMAT can be improved by a ferrite back-plate [4]. But it only improves the performance of generating efficiency. The EMAT receiving efficiency is still affected by lift-off. It is reported that the amplitude of received signal is inversely proportional to the square of lift-off [5]. A variable gain amplifier whose gain can be adjusted according to the lift-off can be used to reduce the signal attenuation. But the active variable gain amplifier adds noise to the signal, and the control of the gain adjusted by lift-off is complex and is hard to put into practice. This paper describes a method using voltage resonance as a variable gain amplifier to improve the lift-off performance of receiving EMAT. The gain of voltage resonance can be adjusted automatically with lift-off and don’t make obviously change to the signal.

2. Principle
A voltage resonant circuit in receiving EMAT is constituted by a coil and a capacitor. The coil in receiving EMAT can treat as an equivalent voltage source, an equivalent inductor and an equivalent resistor in series. The equivalent voltage source outputs the detected
ultrasonic signals. The schematic diagram of voltage resonance in the receiving EMAT is shown in Figure 1. The equivalent series resistance of capacitor is very small compared with equivalent resistance of coil, so it is ignored. The output voltage of the voltage resonant circuit is equal to the voltage across the capacitor. The gain of voltage resonance is given by

\[
G_{VR} = \frac{1}{\omega C_R} \frac{1}{\sqrt{R_{eq}^2 + (\omega L_{eq} - \frac{1}{\omega C_R})^2}}
\]

(1)

Where \( L_{eq} \) is the equivalent inductance shown in Figure 1, \( R_{eq} \) is the equivalent bulk resistance of coil, \( C_R \) is the capacitance of connected capacitor, and \( \omega \) is the angular frequency of ultrasonic signals. Regarding to a given impedance of coil, voltage resonant circuit gets the maximal gain when the capacitance is satisfied by

\[
C_R = \frac{1}{\omega^2 L_{eq}}
\]

(2)

The maximal gain is equal to quality factor of the voltage resonant circuit at the frequency of ultrasonic signal. The quality factor is give by

\[
Q = \frac{\omega L_{eq}}{R_{eq}}
\]

(3)

![Figure 1 Schematic diagram of voltage resonance in receiving EMAT](image)

For a given receiving EMAT enhanced by voltage resonance, the capacitance is constant, but the impedance of receiving coil is varied with lift-off. So the gain of voltage resonance is changed due to the lift-off at the frequency of ultrasonic signal. When the capacitance is advisable, the variable gain can be used to compensate the attenuation of signal cause by lift-off.

When the lift-off is increased, the equivalent bulk resistance of receiving coil will decrease and the equivalent inductance of receiving coil will increase. According to the Equation 1, the gain of voltage resonance increase with the reduction of the difference of reactance between the capacitor and the coil. So the reactance of capacitor should bigger than the reactance of receiving coil. But a too big capacitance weakens the maximal gain of voltage resonance at frequency of ultrasonic signal. The suitable capacitance can be calculated by Equation 2, where \( L_{eq} \) is inductance of the coil at a high lift-off. When the lift-off is lower than this lift-off, the gain will increase with the lift-off to restrain the attenuation.

3. Experiment

3.1 Experiment Setup
To measure the impedance of receiving coil in different lift-off and the lift-off performance of receiving EMAT, a bulk shear wave pitch-catch experiment is setup as shown in Figure 2. The generation EMAT is fixed on the bottom of a steel sample. The receiving coil is held above a fixed location on the top of the sample, allowing only vertical adjustments of lift-off from the sample. The receiving coil and generation EMAT are in-line at acoustic axis to avoid signal reduction cause by misalignment. The permanent magnet is at the top of receiving coil. The thickness of steel sample is 40mm.

The receiving coil is 25mm in diameter, single layer spiral coil made by printed circuit board. The coil of this type is one of the most efficient coil designs for receiving perpendicular shear waves. The receiving coil to sample lift-off distance is able to be adjusted in a range from 0mm to 6mm with 0.2mm steps.

The generation EMAT is driven by a tone burst of the frequency of 2.5MHz and cycles of 12. The driving current is up to 10A in amplitude.

![Figure 2 Experimental setup to investigate the lift-off performance](image)

3.2 Impedance Measurements

The impedance of receiving coil is measured by a WK 6500B Precision Impedance Analyzer in the lift-off range from 0mm to 6mm with 0.2mm steps. The results are shown in Figure 3. When the coil is close to the sample surface, the resistance and the inductance vary with lift-off obviously. The change rates of resistance and inductance are reduced as the increase of lift-off. The impedance of receiving coil is almost constant in the range from 5mm to 6mm. It is considered that the impedance of the coil suffers little influenced by the steel sample at the lift-off of 6mm and nearly doesn’t vary with lift-off.
According to the impedance of the receiving coil in the range from 0mm to 6mm, a suitable capacitance for the coil is calculated by using the inductance at 6mm lift-off and the value is 1075pF. The gain calculated by Equation 1 in the range from 0mm to 6mm is shown in the Figure 4. It is shown that the gain is increase with lift-off, and the voltage resonance also amplifies the signal with the gain of 2 at the 0mm lift-off.

3.3 Experimental results

The capacitor of 1075pF doesn’t exist in practical capacitor, so a capacitor of 1000pF is used in Lift-off performance testing. The signal detected by EMAT enhanced by voltage resonance is similar to the signal detected by conventional EMAT which doesn’t use the voltage resonance. The waveforms of two signals detected at 0mm lift-off is shown in Figure 5. The voltage resonance doesn’t affect the waveform of signal and makes a 100% improvement in peak-to-peak signal amplitude at 0mm lift-off. The gain at 0mm lift-off agrees with the gain of voltage resonance shown in Figure 4.
Using the change of detected signal amplitude to evaluate the lift-off performance of receiving EMAT, the attenuation curve of voltage resonance enhanced receiving EMAT in a range from 0mm to 6mm is shown in Figure 6. For contrast, the attenuation curve of the conventional receiving EMAT is shown in Figure 6 too. For consistency, the amplitude shown in Figure 6 is normalized to emphasize the change of amplitude due to lift-off.

It is shown that the amplitude of signal detected by the conventional receiving EMAT is inversely proportional to the square of lift-off. The amplitude reduces quickly at low lift-off and any change of lift-off makes the variation of amplitude.

The voltage resonance enhanced receiving EMAT exhibits a low sensitivity to lift-off. The amplitude is almost a constant in the range from 0mm to 1.2mm. The amplitude of signal attenuates slowly and these are 24% amplitude left at 6mm lift-off compared with the amplitude at 0mm lift-off.

4. Conclusion
The lift-off performance of receiving EMAT can be improved by a voltage resonance. It is only need a capacitor connected to the receiving coil in parallel. The voltage resonance works as a variable gain amplifier to increase gain with lift-off. Experimental results indicate that the amplitude of detected signal is less sensitive to lift-off variations, especially at low lift-off.

The choice of the capacitance is very important to the voltage resonance. The capacitance should make the gain of voltage resonance increase with lift-off. It is recommended that the reactance of capacitor is equal to the reactance of the receiving coil at a high lift-off at ultrasonic frequency.

The voltage resonance enhanced receiving EMAT has a good lift-off performance and simple structure. It has practical value in the application of EMAT inspection.

Acknowledgements

The authors gratefully acknowledge the financial support from National Key Technology R&D Program of China (No. 2011BAK06B04).

References