International Journal of Applied Electromagnetics and Mechanics 64 (2020) 493–500
DOI 10.3233/JAE-209356
IOS Press

The influence of magnetic head's pose on magnetic flux leakage detection

Jian Tang, Rongbiao Wang, Jikai Zhang and Yihua Kang*
State Key Lab of Digital Manufacturing Equipment & Technology, Huazhong University of Science and Technology, Wuhan, China

Abstract. As a high-sensitivity magnetic sensor, the magnetic head has been gradually applied to non-destructive testing. Compared with the single coil and the coil with an iron core, the magnetic core can converge the weak leakage magnetic field because it can form a magnetic circuit to transmit the leakage field to the coil wound thereon. So that it has a higher sensitivity. However, in practical applications, it's found that the pose error of the head affects its sensitivity. Therefore, this paper analyzes the influence of the tilt of the head on the magnetic core's ability to sense leakage magnetic field, and then the influence is verified by simulations and experiments. The study finds that, when tilted around two horizontal axes, the larger the tilt angle is, the larger the signal is. When tilted around the vertical axis, the larger the tilt angle is, the smaller the signal is.

Keywords: Magnetic head, coil, sensor, magnetic flux leakage (MFL) testing, nondestructive testing (NDT)

1. Introduction

Magnetic flux leakage (MFL) testing has been widely used in the petroleum industry and the automobile industry [1–4], because it can meet needs of high-speed and high-precision detection, and is easy to automate [5–7]. In recent years, with increasing requirements of detection accuracy, a series of MFL sensors with higher sensitivity have been developed, such as AMR, GMR, and TMR [8]. However, these sensors have a small linear range, which cannot be used under the high background magnetic field strength. Coil-based sensors cannot be saturated, because it measures the variation of magnetic field. Therefore, new coil-based MFL sensors still have great research potential.

As shown in Fig. 1, single coil can only pick up an open, wide range leakage magnetic field instead of a weak, local magnetic field. In order to increase the leakage flux in the coil and improve the sensitivity, a columnar iron core is placed in the coil. The high permeability core can converge the leakage magnetic field into the core interior. So, the coil can sense more leakage flux. It significantly improves the sensitivity of the sensor [2]. Nevertheless, there is still much air in the magnetic circuit of leakage flux, and the magnetic resistance is high. E. Li proposed a magnetic bridge method in MFL of high sensitivity [9]. Then, J. Wu detected the micro-crack on the bearing using the magnetic head successfully and studied the optimal opening gap of the magnetic head [1].

*Corresponding author: Yihua Kang, State Key Lab of Digital Manufacturing Equipment & Technology, Huazhong University of Science and Technology, Wuhan, China. E-mail: yihuakang@mail.hust.edu.cn.

Fig. 1. Single coil, iron-core coil and magnetic head.

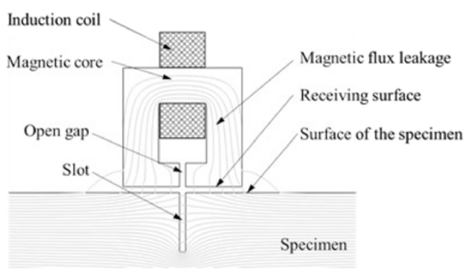


Fig. 2. Principle of magnetic head.

In practice, in order to protect the smooth surface, sometimes, the sensor is prohibited from touching the surface. The gap between the sensor and the specimen is called lift-off. Since the MFL signal amplitude attenuates exponentially as the lift-off increases, the lift-off is usually not more than 0.5 mm in micro-crack detection. However, due to machining errors and positioning errors, there are always various deviations in the pose of the head [10,11]. Furthermore, due to its high sensitivity, it will have a certain influence on the signal when the head's pose changes. On the one hand it affects the accuracy in quantitative detection, and on the other hand it leads to consistency problems in the array sensor. Therefore, it is necessary to study the influence of magnetic head's pose in MFL detection.

2. Principles and analysis

As shown in Fig. 2, the magnetic head is composed of a magnetic core and a coil which is wound around the core. In the MFL test, the magnetizer magnetizes the specimen to a saturated state, and the magnetic head scans the surface. When there is a defect, the magnetic field will leak out of the specimen and the leakage field is gathered by the core. The magnetic flux in the coil changes, and the coil outputs an electrical signal. Compared with single coil or iron-core coil, the head has two receiving faces, one in and one out, which makes the core form a complete magnetic circuit for the leakage field. Air in the magnetic circuit is little, and the magnetic resistance is small. So that the leakage flux passing through the coil increases and the sensitivity improves. This is the detection principle of the magnetic head.

In order to facilitate the study, various pose changes are divided into three directions tilt of X, Y and Z, as shown in Fig. 3. However, once the head tilts, the vertical distance from every point on the receiving surface of the head to the surface of the specimen will no longer be the same, and the lift-off cannot be determined. Therefore, the average vertical distance from each point on the receiving surface to the specimen surface is defined as the average lift-off. When the average lift-off is constant, the influence of the overall lift-off change can be avoided in the study. Therefore, in this paper, regardless of the tilt direction, the vertical distance from the center point of the receiving surface to the detecting surface is constant, so that the average lift-off of the magnetic head can be unchanged.

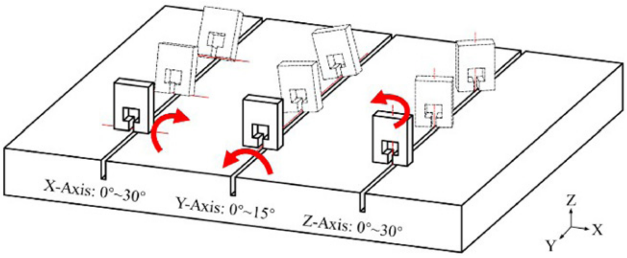


Fig. 3. Heads are tilted around three directions: X, Y and Z.

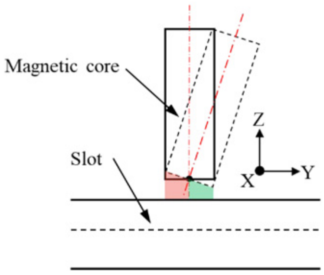


Fig. 4. The head tilted around the X-axis.

2.1. X-axis tilt analysis

For the tilt around X-axis, as shown in Fig. 4, the lift-off change of each point on the receiving surface can be divided into two parts on both sides of the midpoint. The lift-off of the left part becomes larger, as marked in red. Simultaneously, the lift-off of the right part reduces, as marked in green. Due to symmetry, these two parts are completely complementary. Any point on the left part whose lift-off increases by a, there is a corresponding point in the right part whose lift-off decreases by a. The receiving surface senses the vertical component of the leakage magnetic field H_z. According to the magnetic dipole model [12], the expression of H_z is shown in the Eq. (1):

$$H_z = \frac{H_0}{2\pi} \ln \frac{[(y+b)^2 + (z+h)^2][(y-b)^2 + z^2]}{[(y+b)^2 + z^2][(y-b)^2 + (z+h)^2]}, \tag{1}$$

where H_0 is the magnetic field inside the slot and is related to the magnetic charge density and the permeability of the specimen. The magnetic field strength is a constant for the charge density which is equivalent on both flanks. The width and the depth of the defect are $2b$ and h, respectively. The coordinate of a detecting point is (y, z). When $2b$, h and x were 0.5 mm, 2 mm and 0.6 mm, the curve of H_z is shown in Fig. 5. As the lift-off increases, H_z will decrease exponentially, which is a concave function. According to the characteristic of the concave function,

$$f(x) - f(x+a) \leq f(x-a) - f(x). \tag{2}$$

That is to say, the increased magnetic field strength due to the decrease of the lift-off value is greater than the decreased magnetic field strength due to the increase of the lift-off value. Therefore, the magnetic field induced by the whole receiving surface increases as the tilt angle increases.

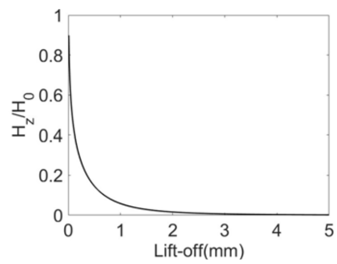


Fig. 5. Relationship between vertical component of leakage magnetic field and lift-off.

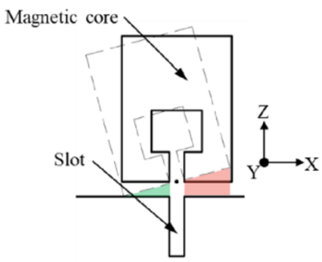


Fig. 6. The head tilted around the Y -axis.

2.2. Y-axis tilt analysis

For the tilt around Y -axis, as shown in Fig. 6. Based on Hopkinson's law, the magnetic flux in the detection magnetic circuit is expressed as follows:

$$\Phi_{mr} = F/(R_{t\alpha} + R_{mh}), \tag{3}$$

where F is the magnetomotive force depending on the defect size and the magnetization intensity in the materials. The magnetic flux $\boldsymbol{\Phi}_{mr}$ flows in the magnetic core whose magnetic reluctance is R_{mh}, and the magnetic reluctance of the air gap is $R_{t\alpha}$. R_{mh} is a fixed value. Therefore, the greater the $R_{t\alpha}$ is, the smaller the $\boldsymbol{\Phi}_{mr}$ is, and the weaker the ability of the magnetic core to collect leakage magnetic field is.

The leakage magnetic field passes through the air from the left side of the defect to the left end of the core. After passing through the core interior, the magnetic field exits from the right end of the core and enters the air gap. Finally, the magnetic field returns to the right side of the defect. The magnetic reluctance of the air gap $R_{t\alpha}$ is divided into two parts, the red part $R_{r\alpha}$ and the green part $R_{g\alpha}$, as shown in Fig. 6. Because the length of magnetic reluctance of every integral element of the two parts is not uniform, we should integrate the magnetic reluctance of the air gap. The magnetic reluctances of red part and green part are in series, while integral elements in green part interior or red part interior are in parallel. So, the magnetic reluctance of the air gap is expressed as follows:

$$\begin{aligned} R_{t\alpha} &= R_{g\alpha} + R_{r\alpha} = 1\Big/\!\!\Big/\int_{-0.5b\cos\alpha}^{0} 1/R_{g\alpha i}\,\mathrm{d}x + 1\Big/\!\!\Big/\int_{0}^{0.5b\cos\alpha} 1/R_{r\alpha i}\,\mathrm{d}x \\ &= \frac{\tan\alpha}{\mu d\cdot\ln[h/(h-0.5b\sin\alpha)]} + \frac{\tan\alpha}{\mu d\cdot\ln[(h+0.5b\sin\alpha)/h]}, \end{aligned} \tag{4}$$

where b, α, $R_{g\alpha i}$, $R_{r\alpha i}$, μ, d, h are the width of the core, the tilt angle, the reluctance of integral element of green part, the reluctance of integral element of red part, the permeability of air, the thickness of the

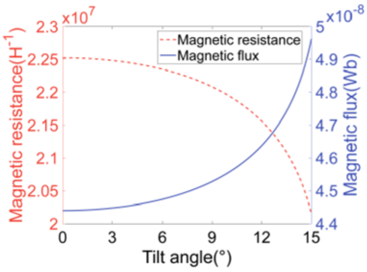


Fig. 7. Relation between air magnetic reluctance/magnetic flux and tilt angle.

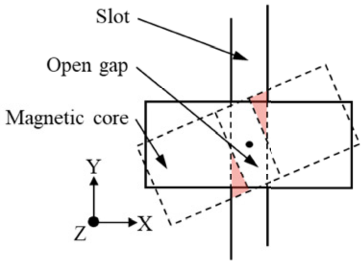


Fig. 8. The head tilted around the Z axis.

core and the average lift-off, respectively. When b = 3.7 mm, h = 0.5 mm, μd = 2.4 $\times 10^9$ H, the curve of Eq. (4) is shown in Fig. 7. We can see that, as the tilt angle increases, the resistance of the air gap, decreases, as plotted in red line, and the magnetic flux in the magnetic circuit, increases, as plotted in blue line. Therefore, the magnetic flux into the receiving surface increases as the tilt angle increases.

2.3. Z-axis tilt analysis

For the tilt around Z-axis, there is no change in lift-off, as shown in Fig. 8. However, the leakage flux entering the core is also related to the distribution of the leakage field itself. It is the vertical component of the magnetic field H_z that the magnetic core senses. It can be obtained according to Eq. (1), as shown in Fig. 9. From both sides to the origin, after passing x_1 and x_2, respectively, the closer to the origin, the smaller the absolute value of H_z is. After crossing the origin, the H_z increases inversely.

With the tilt angle around Z-axis increasing, the receiving surfaces on both sides gradually approach the center plane of the defect, as shown in the red area in Fig. 8. As analyzed above, the closer to the center plane of the defect, the smaller the H_z is. As the angle increases, the area that passes over the center plane begins to receive the reverse magnetic field. Therefore, the larger the tilt angle is, the less the magnetic flux in the core.

3. Finite element simulation

The geometric parameters of the simulation model are shown in the Fig. 10. The specimen material is soft iron, whose relative permeability is 400, and there is a rectangular slot defect. The residual magnetic flux density of the two permanent magnets is 1 T, and the specimen is longitudinally magnetized with the

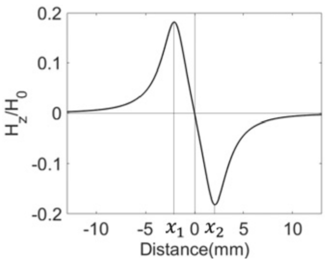


Fig. 9. Distribution of the vertical component of the leakage magnetic field.

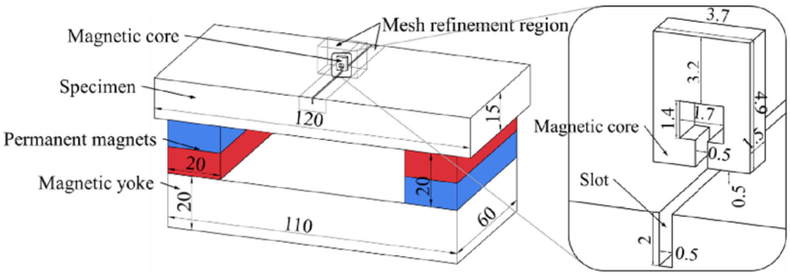
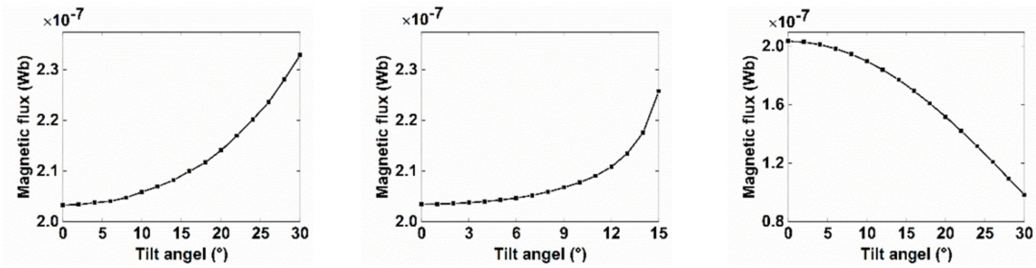


Fig. 10. Simulation model.



(a) Tilt around X-axis (b) Tilt around Y-axis (c) Tilt around Z-axis

Fig. 11. The simulation results.

yoke. The magnetic core is soft iron with a relative permeability of 50,000 and placed in the center of the rectangular slot.

To avoid the core contact with the specimen, the range of tilt around X-axis is set to 0° ~30°, around Y -axis is set to 0° ~ 15°. The range of rotation around Z-axis is set to 0° ~ 30°, which is same as X-axis, as shown in Fig. 3. The normal component of the magnetic flux density at each point on the cross section of the central of the core is extracted, and the leakage magnetic flux passing through the cross section is the surface integral of the normal component. The data obtained from tilts around X-axis, Y -axis and Z-axis are plotted, respectively. The simulation results are shown in the Fig. 11.

Simulation results show that, when the head tilts around the X-axis, the larger the tilt angle, the more the magnetic flux in the core; when tilts around the Y -axis, the larger the tilt angle, the more the magnetic flux in the core; when tilts around the Z-axis, the larger the tilt angle is, the less the magnetic flux in the core is, which is in agreement with the theoretical analysis.

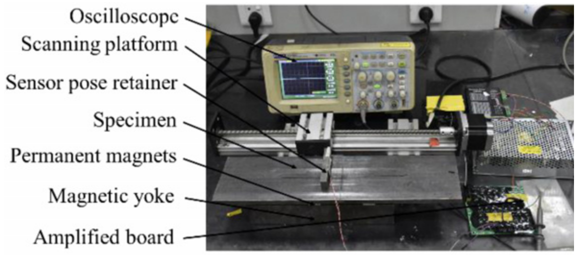


Fig. 12. Experimental platform.

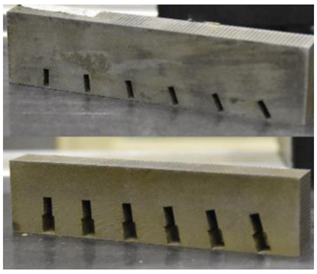


Fig. 13. Sensor pose retainers.

4. Experiment

The experimental platform is shown in the Fig. 12. The magnetic head consisted of a 300 turns coil and a magnetic core made of permalloy with an opening gap of 0.5 mm. The specimen was a Q235 steel plate with a length, width and height of 120 mm, 60 mm and 15 mm. The laser was used to process the defect (width 0.5 mm, depth 2 mm). Two NdFeB magnets were used as magnetizers, which were connected with a yoke made of Q235.

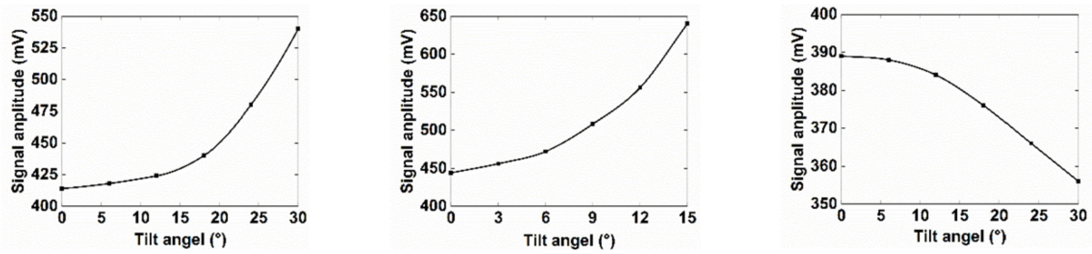
In the experiments of X-axis and Y -axis, it was hard to guarantee the tilt angle and the lift-off value. To ensure the specific pose of the head during scanning, different pose retainers were made of stainless steel, as shown in Fig. 13. In the experiment, the head was placed into specific slot of the pose retainer in turn. And only the bottom surface of the pose retainer needed to be attached to the detecting surface closely to ensure that the head's pose was constant.

In the experiment, the screw nut slide was used to ensure the constant scanning speed, and the speed was set to 200 mm/s. The scan direction was perpendicular to the crack. The experimental results are shown in the Fig. 14.

The experimental results prove that, as the tilt angle increases, the peak-to-peak value of the signal around X-axis and Y -axis increases, and the peak-to-peak value around Z-axis decreases. It further verifies the analysis and simulation results.

5. Conclusion

This paper expounds the influence of the tilt of magnetic head around three orthogonal directions on the signal in the MFL test. When the average lift-off is constant, as the tilt angle increases around the X-axis or Y -axis, the leakage flux received by the magnetic head increases, and the signal amplitude increases.



(a) Tilt around X axis (b) Tilt around Y axis (c) Tilt around Z axis

Fig. 14. Experimental results of the influence of tilt around different directions on detection ability.

As the tilt angle increases around the Z-axis, the leakage flux received by the magnetic head decreases, and the signal amplitude decreases.

Generally, when using magnetic head for precise MFL detection, attention should be paid not only to conventional lift-off value, but also to the rotational freedom to ensure accurate positioning.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (NNSFC) [51907131, 51875226] and National Key R&D Program of China (Grant No. 2018YFB0106000).

References

[1] J. Wu, Y. Yang, E. Li et al., A high-sensitivity MFL method for tiny cracks in bearing rings, *IEEE Transactions on Magnetics* **54**(6) (2018), 1–8.
[2] J. Wu, H. Fang, L. Li et al., A lift-off-tolerant magnetic flux leakage testing method for drill pipes at wellhead, *Sensors* **17**(1) (2017), 201.
[3] D. Premel, E.A. Fnaeich, S. Djafa et al., Simulation of magnetic flux leakage: application to tube inspection, *Review of Progress in Quantitative Nondestructive Evaluation* **1430** (2012), 1918–1925.
[4] Y. Kang, J. Wu and Y. Sun, The use of magnetic flux leakage testing method and apparatus for steel pipe, *Materials Evaluation* **70**(7) (2012), 821–827.
[5] Y. Sun and Y. Kang, Magnetic mechanisms of magnetic flux leakage nondestructive testing, *Applied Physics Letters* **103** (2013), 184104.
[6] Z.D. Wang, Y. Gu and Y.S. Wang, A review of three magnetic NDT technologies, *Journal of Magnetism and Magnetic Materials* **324**(4) (2012), 382–388.
[7] A. Sophian, G.Y. Tian, D. Taylor et al., Electromagnetic and eddy current NDT: a review, *Insight* **43**(5) (2001), 302–306.
[8] S. Hainz, E. de la Torre and J. Guttinger, Comparison of magnetic field sensor technologies for the use in wheel speed sensors, in: *2019 IEEE International Conference on Industrial Technology*, 2019, pp. 727–731.
[9] E. Li, Y. Kang, J. Tang et al., A new micro magnetic bridge probe in magnetic flux leakage for detecting micro-cracks, *Journal of Nondestructive Evaluation* **37**(3) (2018), 37–46.
[10] X. Huang, J. Wu, J. Wang et al., Signal characteristics of circular induction coil influenced by scanning spatial location in MFL, *Materials Evaluation* **76**(12) (2018), 1647–1659.
[11] J. Wu, Y. Sun, Y. Kang et al., Theoretical analyses of MFL signal affected by discontinuity orientation and sensor-scanning direction, *IEEE Transactions on Magnetics* **51**(1) (2015), 1–7.
[12] C. Edwards and S. B. Palmer, The magnetic leakage field of surface-breaking cracks, *Journal of Physics D: Applied Physics* **19**(4) (1986), 657–673.