

Low-power eddy current detection with 1-1 type magnetoelectric sensor for pipeline cracks monitoring



Zhaoqiang Chu^{a,c,d}, Zekun Jiang^{a,c,d}, Zhineng Mao^{a,c,d}, Ying Shen^{a,c,d}, Junqi Gao^{a,c,d,*}, Shuxiang Dong^{b,*}

^a Acoustic Science and Technology Laboratory, Harbin Engineering University, Harbin 150001, China

^b Department of Materials Science and Engineering, College of Engineering, Peking University, 100871, Beijing, China

^c Key Laboratory of Marine Information Acquisition and Security (Harbin Engineering University), Ministry of Industry and Information Technology, Harbin 150001, China

^d College of Underwater Acoustic Engineering, Harbin Engineering University, Harbin 150001, China

ARTICLE INFO

Article history:

Received 29 September 2020

Received in revised form 1 December 2020

Accepted 10 December 2020

Available online 16 December 2020

Keywords:

Magnetoelectric sensor

Nondestructive testing

Eddy current

ABSTRACT

Pipeline systems, such as oil and natural gas pipelines, which are normally buried underground or distributed under the sea, are susceptible to corrosion and pressure destruction, and hence timely and reliable nondestructive testing (NDT) is necessary. Conventional nondestructive testing methods are generally based on ultrasonic, eddy current and magnetic flux leakage mechanism. With respect to eddy current testing (ECT) technologies, the current challenge is to develop magnetic sensors with high detection ability, extremely low power consumption and compatible with Internet of Things (IoT). Giant resonant magnetoelectric (ME) coupling has been previously reported in our proposed 1-1 ME composites. Here, we further presented an investigation on the eddy current testing (ECT) using 1-1 type ME sensor. The proposed ECT probe was built by integrating a small exciting coil surrounding the ME sensor. Simulation results indicate ECT based on ME sensors is especially applicable for non-ferromagnetic and low-conductivity materials, e.g. steel. One-dimensionally distributed cracks with varying crack sizes in a steel pipeline was then experimentally identified and located using ECT method. More importantly, the power consumption of our proposed ECT probe is as low as 0.625 μ W, which shows 2–3 orders of magnitude improvement compared with other probes based on e.g. magnetoresistive (MR) sensors. Our research here provides a fundamental insight into NDT using ME sensors as a ECT probe and represents a crucial step towards online low-power monitoring of pipeline cracks.

© 2020 Elsevier B.V. All rights reserved.

1. Introduction

Nowadays, a great number of oil and natural gas pipelines are buried underground and distributed under the sea. These pipeline systems are susceptible to corrosion and pressure destruction. It is well-known that small flaws and cracks in a pipeline could cause serious accidents and economic loss in the case of no timely and reliably nondestructive detection. Therefore, researchers around the world are racing to investigate pipeline inspection technologies to estimate and evaluate the condition of a working pipeline [1–3]. Common nondestructive testing (NDT) methods are generally based on ultrasonic [1,4,5], eddy current [2,6–8] and magnetic

flux leakage mechanism [3,9–11]. In the case of underground and undersea environment, ultrasonic inspection is not viewed as an effective means due to the contacting requirement and high power consumption. In addition, solutions based on ultrasound detection are highly dependent on physical properties of sound waves and are less effective for surface defects on the examination side. The magnetic flux leakage (MFL) testing method is specifically limited to ferromagnetic tubes, such as the well-known pipeline pigs, while ECT could be employed for conductive but non-ferromagnetic materials, e.g. aluminum and steel, which are normally preferred in engineering applications [12]. More importantly, ECT maintains high resolution for surface detection without removing protective paint or coating, and delivers results almost immediately. Compared with eddy current inspection technologies, high excitation field is also inevitably required in magnetic flux leakage approach to saturate the pipe wall and thereby leads to high power consumption [2,3]. With respect to eddy current testing (ECT) technologies,

* Corresponding authors.

E-mail addresses: gaojunqi@hrbeu.edu.cn (J. Gao), sxdong@pku.edu.cn (S. Dong).

the current challenge is to develop magnetic sensors with economical cost, miniaturized dimension and high detection sensitivity. In addition, low-power even self-powered ECT probe is also highly desired considering the demand for wireless ECT networks.

Magnetic field sensors based on anisotropic magneto-resistance (AMR) [13], giant magneto-resistance (GMR) [14,15], tunnel magneto-resistance (TMR) [12,16], giant magneto-impedance (GMI) [17] and conventional induction coils have been widely studied and utilized to implement ECT for nondestructive cracks detection [18]. The advantages of magneto-resistive (MR) sensors over conventional induction coils are the enhanced spatial resolution, higher detection sensitivity and smaller mutual inductance. Note that the state-of-the-art TMR sensor has sensitivity of 7.2 pT/√Hz @ 10 Hz and around 100 pT/√Hz @ 1 Hz [16]. It is now available to get the limit of detection of magnetic field sensor below 10 pT/√Hz @ 1 Hz by using flux-gate magnetometer, SQUID magnetometer and optically pumped magnetometer. But either the high power consumption, the huge system size or the unacceptable cost of those sensors results in disadvantages in terms of spatial resolution and customized design. In this regard, it is of great importance to develop new magnetic sensors by taking into account of overall performance, i.e. sensitivity, power consumption, size, cost and the compatibility with future Internet of things (IoT) system.

Investigations into the magnetoelectric (ME) coupling effect, which enables interactions between magnetization and polarization in single-phase or composite materials, have made enormous progress and provide diverse routes to new functional device architectures, including magnetic sensors and magnetic inductions antennas [19–24]. In terms of power consumption and limit of detection, previous reports show ME sensors do have advantages over magneto-resistive sensors. In 2011, Wang et al. reported an extremely low equivalent magnetic noise of 5.1 pT/√Hz at 1 Hz based on 2-1 typed magnetoelectric composites [25]. By using multi-L-T and passive working mode, the measured equivalent magnetic noise of the Metglas/Mn-PMNT composite was measured as low as 0.87 pT/√Hz at 30 Hz [26]. In contrast to passive magnetic detection, quasi-static or extremely-low frequency magnetic field can be more effectively detected by using frequency-conversion techniques in active ME sensors. For example, Chu et al. reported an enhanced low-frequency magnetic field sensitivity in 1-1 typed magnetoelectric composite via amplitude modulation method and the measured magnetic field resolution was as low as 100 pT at 0.1 Hz [27]. It should be particularly mentioned that extremely high ME coupling coefficient and thus an enhanced magnetic field detection ability can be obtained based on electromechanical resonance (EMR) enhancement phenomenon, which makes ME sensors highly competitive over other magnetic field sensors, e.g. fluxgate sensors and optically pumped magnetometers [28]. The directly measured detection resolution of 1-1 ME sensor was found to be 135 fT at the resonance frequency of ~23 kHz [29]. But, resonance ME magnetic field sensors are not studied and employed as widely as low-frequency magnetic sensor due to the narrow bandwidth ~100 Hz. In the field of eddy current testing, however, the bandwidth is not the limiting factor. But related theoretical and experimental research has been rarely reported.

In this work, we studied the application of magnetoelectric sensor for ECT. First, the magnetoelectric coupling coefficient and the corresponding equivalent magnetic noise of our previously reported 1-1 ME composite was characterized at an open environment. The equivalent magnetic noise at resonance frequency of 23.28 kHz was measured as low as 95 fT/√Hz. Slightly deviating from the exact resonance frequency, the equivalent magnetic noise of ME sensors lowered further to around 65 fT/√Hz. Then an ECT probe was constructed by integrating an exciting coil surrounding the sensor. The EC distribution in the wall of pipelines made from copper, aluminium or steel was simulated and the influence of EC-

induced magnetic field on the excitation field was also studied by finite element modelling. Experimental results verified the simulation analysis and indicated ME ECT probe was able to identify and locate small embedded cracks in a steel pipeline. During the testing, the lift-off distance was kept as 3 mm and the power consumption was only 0.625 μ W, which shows 2–3 orders of magnitude improvement compared with probes based on magneto-resistive (MR) sensors. This preliminary study focusing on ECT based on ME sensors provides new route for pipeline non-destructive testing and expands the application range of ME sensors as well.

2. Testing system

2.1. Noise level and LOD of 1-1 type ME sensor

Our 1-1 typed ME sensor was composed of [011]-oriented $\text{Pb}(\text{Mg}_{2/3}\text{-Nb}_{1/3})\text{O}_3\text{-Pb}(\text{Zr, Ti})\text{O}_3$ (PMN-PZT) single-crystal fiber and amorphous FeBSi alloy (Metglas). It has a dimension of 100 mm \times 1.5 mm \times 1 mm and operates in L-T mode (longitudinally magnetized and transversely poled). The ME coupling coefficient of 1-1 ME composite was studied in detail in our previous articles [29]. Here we further characterized the noise level and analysed the equivalent magnetic noise of 1-1 ME composites. Fig. 1(a) gives the noise power spectrum density (PSD) measured at an open lab environment without shielding. The resonant noise density was around 52 nV/√Hz without applying any bias field and exciting field. When subject to an optimized DC field, however, a sharp peak occurred at the resonance frequency of 23.28 kHz and the noise level increased to 161 nV/√Hz, which is 3 times as high as the noise level when closing the DC current supply. The external noise source from DC current supply could increase the noise density at the whole frequency band. It was also found the inherent noise level in ME composite increased as well, particularly at the resonant frequency, which is of great importance when considering the resonance magnetic detection capability. As provided in Fig. 1(b), the resonant ME coupling coefficient α_{ME} was measured as high as 8800 V/cm*Oe with optimized DC bias. Correspondingly, the equivalent magnetic noise (EMN), which indicates the limit of detection (LOD) for 1-1 ME composites, was calculated by the following expression,

$$LOD = \frac{\text{Noise PSD}}{\alpha_{ME} * t} \quad (1)$$

where PSD is the noise power spectrum density, α_{ME} is the magnetoelectric coefficient, t is the thickness of piezoelectric crystal.

As shown in Fig. 1(b), LOD at the exact resonance frequency is

$$\frac{161 \text{ nV}/\sqrt{\text{Hz}}}{8800 \text{ V}/(\text{cm}^* \text{Oe}) \times 0.02 \text{ cm}} = 95 \text{ fT}/\sqrt{\text{Hz}}$$

Note the thickness of PMN-PZT crystal is 0.02 cm. But when looking at the frequencies slightly deviating from the exact resonance frequency, the equivalent magnetic noise of the ME sensor lowered further to around 65 fT/√Hz, while the normal LOD for MR sensors is hundreds of pT level [30]. In addition, one dimensional configuration of our 1-1 ME sensor greatly favors its implementation for practical ECT in the field of NDT for small pipelines in particular.

2.2. ECT probe setup and experimental details

Here, the proposed ECT probe based on 1-1 typed ME sensor for pipeline nondestructive testing is shown in Fig. 2(a). This ECT probe is composed of a 1-1 typed ME sensor and an excitation coil. When this probe is placed in the center of a pipeline and moves along the axial direction of the pipeline, the eddy current is produced flowing within the wall of the pipeline and then generates a secondary magnetic field that tends to weaken the primary magnetic field applied to the ME sensor, see the system setup in Fig. 2(a–b). When a small crack in the wall of a pipeline appears, the locally produced eddy

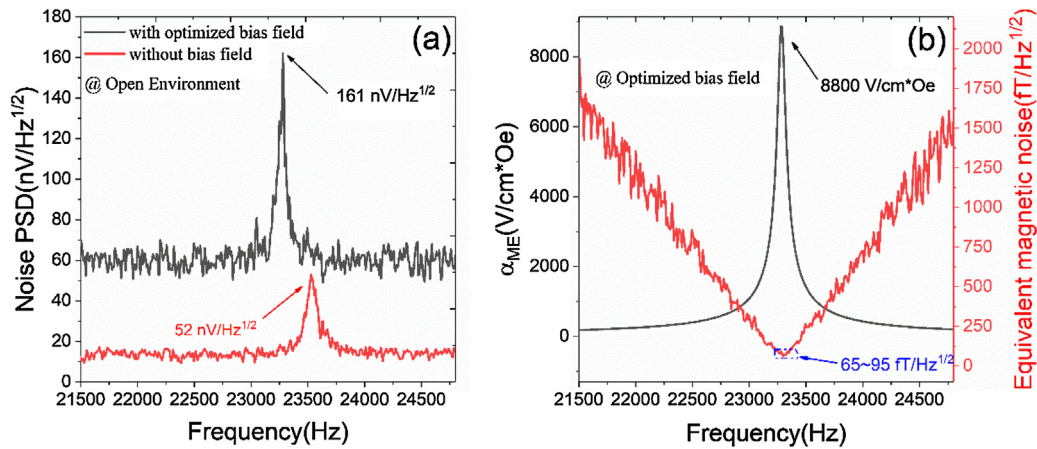


Fig. 1. The frequency dependence of the voltage noise PSD (a), the ME coupling coefficient and the equivalent magnetic noise (b) for 1-1 ME sensor.

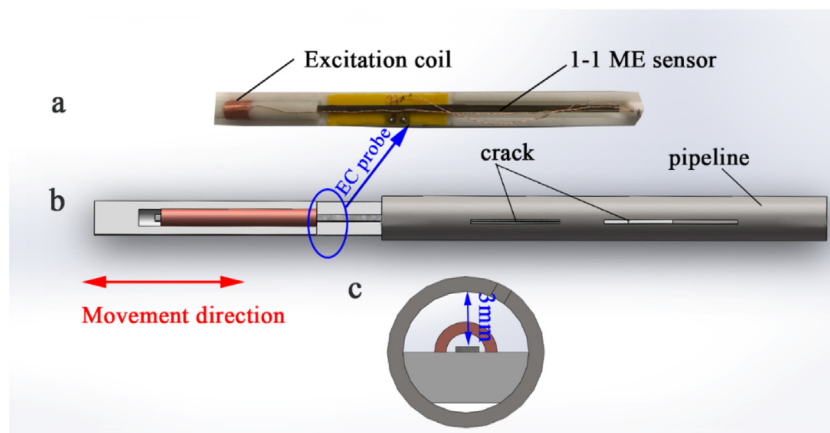


Fig. 2. (a) The prototype of ECT probe. Schematic view of the proposed pipeline NDT system (b) and its cross-sectional building diagram (c).

current will decrease due to the material discontinuity, which in turn results in variation of the final ME voltage output as the summing field increases in this case. Fig. 2(c) gives the cross-sectional building diagram of the system setup and the lift-off distance from the ME sensor to the inner surface of the pipeline is around 3 mm. Conventional ECT probe generally uses magnetic flux concentrator to increase the induced EC intensity and thus to improve the detection sensitivity. But the probe can not be miniaturized in this case and strongly limits its application scenarios. In this work, 1-1 typed ME sensor with one dimensional configuration has a diameter of only 8 mm, which enables the EC probe to be typically utilized for small pipelines. Concerning the detection sensitivity, ME coupling coefficient of the proposed EC probe is the prior factor. With respect to the spatial resolution, the length of excitation coil (5 mm in this work) is then the critical parameter. During the EC testing, the excitation coil is driven by a Function/ Arbitrary Waveform Generator (33522, Agilent, USA) and the driving frequency is close to the resonance frequency of 1-1 ME sensor. The output signal was measured by a lock-in amplifier (SR850, Stanford Research, USA). The optimized bias field was provided by permanent magnets.

3. Results and discussion

3.1. EC simulations

It is well-known the skin effect is a major issue when ECT probe is working at high frequency. EC penetration depth as a function

of working frequency and material parameters can be typically expressed as [2]:

$$\delta = \sqrt{2/(\mu\omega\sigma)} \tag{2}$$

where σ is the conductivity, $\mu = \mu_r\mu_0$ is the magnetic permeability and $\omega = 2\pi f$ is the working angle frequency. Eddy current inspection technologies are susceptible to material properties, i.e., conductivity and permeability. High conductivity and permeability can induce intense eddy current, but it will also inevitably lead to a decrease of the penetration depth, which is a limitation for the eddy current NDT for non-surface or deep cracks. In this work, we compared the most widely used materials, i.e., copper, aluminium and stainless steel. Table 1 summarized the conductivity and the relative permeability for each material. Note we are utilizing the resonant magnetic field detection of 1-1 typed ME sensor in this work. In this regard, the eddy current effect in the vicinity of sensor's resonance frequency is what we care about and focus on. According to Eq. 2, we calculated the penetration depth at 100 Hz and 25 kHz, respectively. It can be seen less conductive 304 L stainless steel exhibits much bigger penetration depth of ~2.7 mm at the frequency of 25 kHz. Table 1 includes the counterparts of amorphous alloy Metglas as well since the piezomagnetic material used in ME sensors will also induce eddy current when driving the sensors at resonance frequency.

Fig. 3 further demonstrated the simulated eddy current distribution in the wall of a pipeline made of copper, aluminium and stainless steel, respectively. As shown in Fig. 3(a), the ME sensor was simplified as a Metglas core. The pipeline with a wall thickness

Table 1
Property parameters for commonly used metal materials.

	Cu	Al alloy	304 L steel	Metglas
Conductivity/($\Omega \cdot m$)-1	$6 \cdot 10^7$	$\sim 3.8 \cdot 10^7$	$1.4 \cdot 10^6$	$7.6 \cdot 10^5$
Relative Permeability	~ 1	~ 1	~ 1	45,000
penetration depth @100Hz	6.49 mm	8.17 mm	42.53 mm	0.27 mm
penetration depth @25kHz	0.41 mm	0.52 mm	2.69 mm	0.017 mm

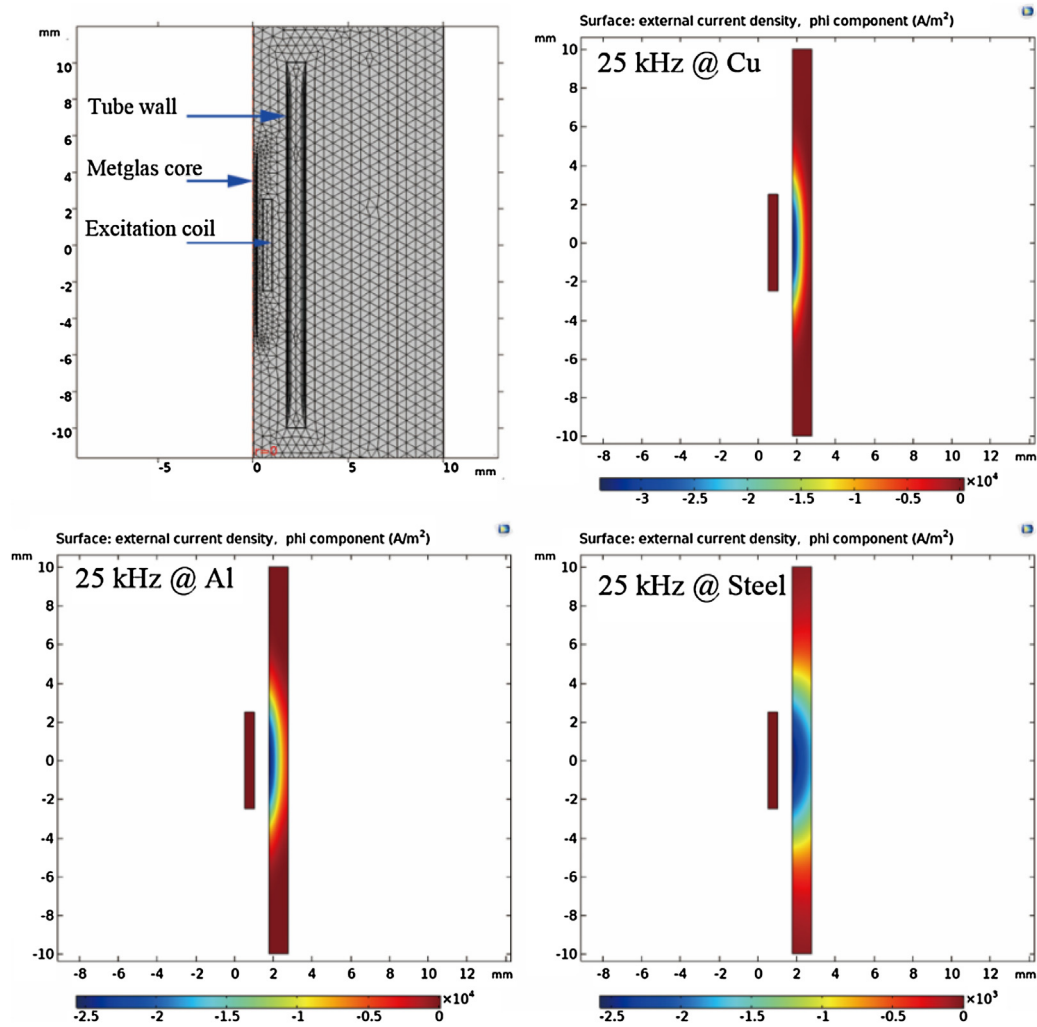


Fig. 3. (a) The simplified simulation model for our proposed ECT system. The simulation results concerning the EC distribution in the wall of the pipeline made from copper (b), aluminium (c), and steel (d) at the driving frequency of 25 kHz. The coil driving current is set as 1 mA.

of 1 mm encircled the internal excitation coil and thereby created an EC distribution with circumferential symmetry. In this case, we could just consider a two-dimensional axisymmetric model. The Z axis is along the axial direction of the pipeline under test. Fig. 3(b-d) then gives the eddy current distribution in the wall of a pipeline made from copper (b), aluminium (c), and steel (d) at the frequency of 25 kHz. Copper and aluminium samples exhibit obvious skin effect and the effective penetration depth is basically less than 0.5 mm. But the induced EC in the stainless steel sample is able to penetrate into the outer surface of the pipeline due to the low conductivity. NDT based on eddy current techniques normally works at frequencies lower than 1 kHz when dealing with aluminium and alloy tubes due to the limitation of penetration depth [12,31]. For non-ferromagnetic and low-conductivity materials, like stainless steel, the working frequency could increase to dozens of kHz. In this case, resonant ME sensors may have great chance to realize highly sensitive ECT. From the perspective of optimizing the work-

ing conditions, it is also of interest and significance to study the eddy current effect in combination with sensor's detection ability at off-resonance frequencies in our coming work.

The frequency dependence of averaged magnetic flux density (Z componnet) in magnetic core is provided in Fig. 4. The eddy current induced magnetic field could counteract and then weaken the excitation field. Fig. 4 shows the sensitive band for copper and aluminium is below 5 kHz, while the frequency response for steel material is basically unchanged at frequencies higher than 10 kHz. The highlighted region is our working frequency band in this work, where the frequency sensitivity for steel is even higher. Different from conventional MR sensors, the resonance frequency of ME sensor can be controlled by applied magnetic field, which is usually termed Delta-E effect. In this regard, the EC-induced magnetic field can not only change the summing field, it is also able to influence the resonance frequency of ME sensors and thereby manipulates the output voltage in a synergistic manner. Based on above simula-

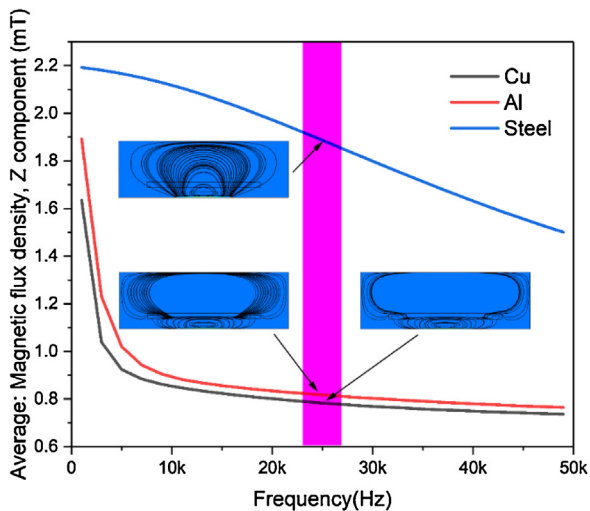


Fig. 4. The frequency dependence of averaged magnetic flux density (Z component) in magnetic core for three kinds of materials. The inset shows the magnetic streamline generated by excitation field and the EC-induced field.

tion analysis, ECT based on ME sensors is especially applicable for non-ferromagnetic and low-conductivity materials.

3.2. EC detection ability

This proposed ECT probe based on ME sensor was examined on pipelines made of copper, aluminium and stainless steel, respectively. Five pipelines with different crack length was used to characterize the crack detection abilities. Those cracks are with the same width (1 mm) and the the same depth (1 mm), while their length was set as 10, 15, 20, 25 and 30 mm, respectively, as shown in Fig. 5(a). During the testing process, the pipeline first approached the excitation coil and moved forward until the coil part was totally encircled by the moving pipeline. Subsequently, the pipeline returned back to the original position. Several seconds later, another kind of pipeline started to repeat the process mentioned above. The testing results were presented in Fig. 5(b–d). Here, the driving current was 1.5 mA and we did not apply any bias field. When the pipeline was keeping away from the driving coil, the ME voltage signal remained at around 0.45 V as shown in Fig. 5(b–d). When the pipeline was approaching, it can be seen that the eddy current effect could sharply decrease the ME voltage output signal. It should be noted that the ME voltage signal in response to the crack length is almost a linear function, as demonstrated in Fig. 5(b–d) with dashed line. Detection sensitivity s , which is defined as $\Delta V/\Delta L$ (V is the output ME voltage and L is the length of a cracks), can be used to assess the EC detection capability in a quantitative manner. When testing a copper pipeline (see Fig. 5(b)), the calculated s is 7 mV/mm. The aluminium pipeline (see Fig. 5(c)) presented a similar response compared with the case in Fig. 5(b) and s was found to be 7.55 mV/mm. Specifically, the ME output voltage decreased from 0.45 V to 0.1 V for aluminium pipeline with a 10 mm crack. In contrast, the eddy current weakening effect was much less obvious with respect to steel pipeline due to the low conductivity. In this regard, we can see that the output ME voltage only decreased to 0.2 V in response to a 10 mm crack, which is almost twice that for an aluminium pipeline (see Fig. 5(d)). As we discussed in Section 3.1, the induced EC is able to penetrate into the outer surface of a steel pipeline due to the low conductivity and also the frequency response for steel is more sensitive. Accordingly, the detection sensitivity of a steel pipeline was calculated to be 8.5 mV/mm, which is even higher than that for a copper or

aluminium pipeline. Those experimental results well-verified the analysis in Section 3.1.

3.3. Crack locating and detecting ability

Finally, the ability to identify and locate small embedded cracks in a pipeline as shown in the insert of Fig. 6 was demonstrated. In a bid to decrease the vibration noise and the lift-off effect [2], our ECT probe was fixed and the testing pipeline was moving along the outer surface of the probe. Different from the experiments as described in Fig. 5, here, we applied an optimized DC bias to increase the AC magnetic field sensitivity for our 1-1 typed ME sensor. The bias field is created by a permanent magnet. Fig. 6(a) gives the measurement result for an aluminum pipeline with a 10 mm crack placed in the center. The scanning signal displayed obvious response to this crack. Note the edge effect was also included in Fig. 6(a), which dramatically lowered the output voltage. Here, the driving current was decreased to as low as 0.25 mA (RMS value) benefiting from the high ME coupling of a 1-1 typed ME sensor at an optimized bias field. The impedance of the excitation coil at the driving frequency is around 10 Ω . In this case, the calculated power consumed by the ECT probe is only 0.625 μ W, which shows 2-3 orders of magnitude improvement compared with ECT probe based on MR sensors. For example, pulsed eddy current detection based on GMR sensor was proposed to detect both surface and sub-surface defects early in 2002 [32]. But the driving peak current reached 300 mA and long-time service would cause local heating and easily introduce temperature fluctuation into the detection system. More recently, Xin'an Yuan et al. reported a synthetic double frequency excitation for detecting both surface and sub-surface defects. Typical defect size is around 10 mm (L)*0.5 mm (W)*2 mm (D). However, the synthetic excitation signal should be amplified by a power amplifier to keep the current amplitude as large as 50 mA and the power consumption in this case was estimated between 10–100 mW [12]. Generally, a magnetic yoke could be used to concentrate the magnetic flux and thereby decrease the excitation current for a NDT system based on MR sensors at a cost of the system size [8].

In order to further compare the crack detection performance, we separately tested an aluminum pipeline and a steel pipeline, respectively, as shown in Fig. 6(b). In both cases, the crack could be successfully recognized and the steel pipeline, complying with the discussion in Section 3.2, also performed enhanced response. Then, one-dimensionally distributed cracks labelled 1# and 2# were machined in an aluminum pipeline and a steel pipeline. The width and depth of those cracks are kept as 1 mm, while the length goes to be 10 mm and 20 mm, respectively. The distance between two cracks is 25 mm. The corresponding measurement result is presented in Fig. 6(c). Specific response to different cracks was obviously obtained and the location was also identified. In theory, we can use either the peak amplitude or the peak width in time domain to characterize the crack dimension. It should be noted here that peak parameters (refer to the amplitude and the width) is also highly related to the scanning speed. The speed was kept the same during the test course in this work. When closely comparing the output response to each material, we found the steel pipeline exhibited higher response and much larger edge effect as well. Because of this, the response peak broadened compared with the case in aluminum pipeline. It should be particularly noted the power consumption for those tests are kept as low as 0.625 μ W, which greatly favored the realization of NDT networks with long-term service. TMR probe has advantage of high spatial resolution (0.1 mm) [33]. However, smaller sensor size means that a greater number of sensors are needed to form an array configuration, which makes the wiring and circuit system more complicated. In this work, the probe based on ME sensor has a one-dimensional configuration consider-

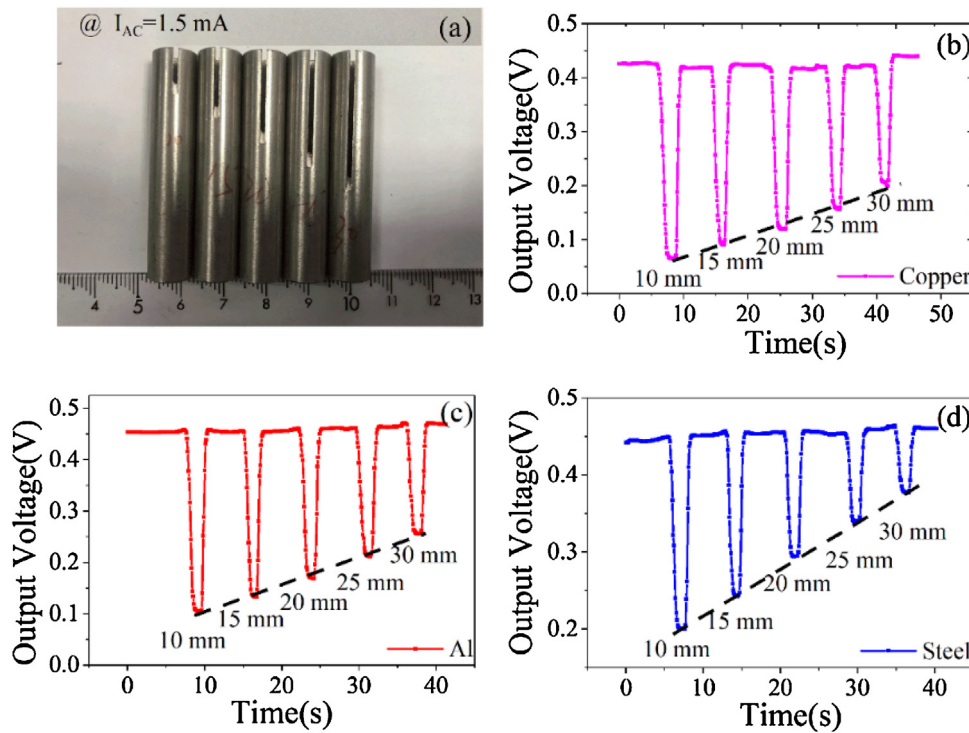


Fig. 5. Crack length detection result. The testing was conducted on copper (b), aluminium (c) and stainless steel pipelines (d), respectively.

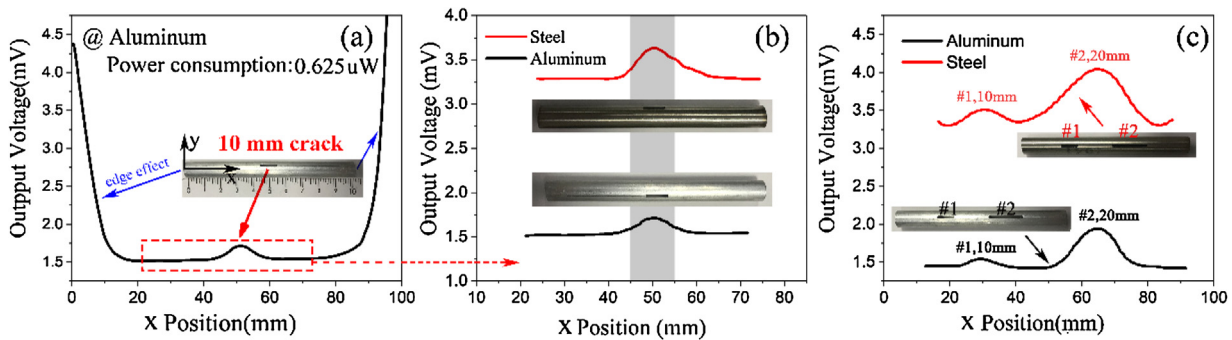


Fig. 6. (a) Measurement signal response for an aluminium pipeline with a 10 mm crack placed in the center. The comparison of crack locating (b) and identifying (c) results in an aluminium pipeline and steel pipeline.

ing the size trade-off, which provides enough resolution for quick inspection of sub-millimeter defect and is typically suitable for small pipelines.

4. Conclusion

In summary, a preliminary research about the low-power eddy current detection for pipeline cracks monitoring using 1-1 ME sensor was systematically demonstrated in this work. Driving close to the resonance frequency, the equivalent magnetic noise of 1-1 ME composites was measured as low as $65 \text{ fT}/\sqrt{\text{Hz}}$. Through simulating the EC distribution and frequency response of the summing field with respect to three kinds of materials, we found our proposed ECT probe is greatly applicable for non-ferromagnetic and low-conductivity materials, e.g. steel. Experimental results showed the crack detection sensitivity for a steel pipeline reached 8.5 mV/mm . One-dimensionally distributed cracks with varying length in a steel pipeline was also experimentally identified and located using our proposed ECT probe. In addition, the power consumption of our probe is measured as low as 0.625 uW , which shows 2–3 orders

of magnitude improvement compared with probes based on magneto-resistive (MR) sensors. Although the crack size in this work is in millimeter scale, we believe this preliminary work will open up a new dimension for the development and application of ECT technologies by using ME sensors. Future work includes the optimization of the excitation coil size, the further decrease of the lift-off distance, the layout design of the NDT system and the final realization of micro-cracks detection.

5. Authorship statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Its submission and publication is approved by all the authors in the list. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in Sensors and Actuators A: Physical.

Author contributions

Zhaoqiang Chu, Junqi Gao and Shuxiang Dong conceived the experiments and prepared the manuscript. Zhaoqiang Chu prepared the samples, modelled the EC distribution and performed ECT experiments. Zekun Jiang and Zhineng Mao performed the noise measurement of 1-1 ME sensor. Zhineng Mao and Yin Shen were involved in the preparation and revision of the manuscript. All authors were involved in the analysis of the experimental and theoretical results.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical reasons.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research work was supported by the National Natural Science Foundation of China (Grant Nos. 51132001, 51072003, and 51772005) and University Free Exploration Support Program (3072020CF0502).

References

- [1] W.M. Alobaidi, E.A. Alkuam, H.M. Al-Rizzo, E. Sandgren, Applications of ultrasonic techniques in oil and gas pipeline industries: a review, *Am. J. Oper. Res.* 05 (2015) 274–287.
- [2] J. Garcia-Martin, J. Gomez-Gil, E. Vazquez-Sanchez, Non-destructive techniques based on eddy current testing, *Sensors Basel (Basel)* 11 (2011) 2525–2565.
- [3] Y. Shi, C. Zhang, R. Li, M. Cai, G. Jia, Theory and application of magnetic flux leakage pipeline detection, *Sensors Basel (Basel)* 15 (2015) 31036–31055.
- [4] Y.Y. Kim, Y.E. Kwon, Review of magnetostrictive patch transducers and applications in ultrasonic nondestructive testing of waveguides, *Ultrasonics* 62 (2015) 3–19.
- [5] H. Miao, Q. Huan, Q. Wang, F. Li, Excitation and reception of single torsional wave T(0,1) mode in pipes using face-shear d24 piezoelectric ring array, *Smart Mater. Struct.* 26 (2017), 025021.
- [6] R. Hamia, C. Cordier, C. Dolabdjian, Eddy-current non-destructive testing system for the determination of crack orientation, *Ndt E Int.* 61 (2014) 24–28.
- [7] H. Shaikh, et al., Use of eddy current testing method in detection and evaluation of sensitisation and intergranular corrosion in austenitic stainless steels, *Corros. Sci.* 48 (2006) 1462–1482.
- [8] L.S. Shuxiang Zhao, Junqi Gao, Jiazeng Wang, Ying Shen, Uniaxial ACFM detection system for metal crack size estimation using magnetic signature waveform analysis, *Measurement* 164 (2020), 108090.
- [9] Y. Gao, et al., Multiple cracks detection and visualization using magnetic flux leakage and eddy current pulsed thermography, *Sens. Actuators A Phys.* 234 (2015) 269–281.
- [10] V. Suresh, A. Abudhahir, J. Daniel, Development of magnetic flux leakage measuring system for detection of defect in small diameter steam generator tube, *Measurement* 95 (2017) 273–279.
- [11] Y. Zhang, Z. Ye, C. Wang, A fast method for rectangular crack sizes reconstruction in magnetic flux leakage testing, *Ndt E Int.* 42 (2009) 369–375.
- [12] Xa. Yuan, et al., Inspection of both inner and outer cracks in aluminum tubes using double frequency circumferential current field testing method, *Mech. Syst. Signal Process.* 127 (2019) 16–34.
- [13] D.F. He, M. Shiwa, J.P. Jia, J. Takatsubo, S. Moriya, Multi-frequency ECT with AMR sensor, *Ndt E Int.* 44 (2011) 438–441.
- [14] Z. Tang, J. Chen, Y. Bai, S. Zhao, Magnetolectric coupling effect in lead-free Bi4Ti3O12/CoFe2O4 composite films derived from chemistry solution deposition, *Smart Mater. Struct.* 25 (2016), 085020.
- [15] W.S. Singh, B.P.C. Rao, S. Thirunavukkarasu, T. Jayakumar, Flexible GMR sensor array for magnetic flux leakage testing of steel track ropes, *J. Sens.* 2012 (2012) 1–6.
- [16] N. Zhang, C. Ye, L. Peng, Y. Tao, Eddy current probe with three-phase excitation and integrated array TMR sensors, *Ieee Trans. Ind. Electron.* (2020), 1–1.

- [17] F. Vacher, F. Alves, C. Gilles-Pascaud, Eddy current nondestructive testing with giant magneto-impedance sensor, *Ndt E Int.* 40 (2007) 439–442.
- [18] J. Hwang, J. Lee, S. Kwon, The application of a differential-type Hall sensors array to the nondestructive testing of express train wheels, *Ndt E Int.* 42 (2009) 34–41.
- [19] S. Salzer, et al., Tuning fork for noise suppression in magnetolectric sensors, *Sens. Actuators A Phys.* 237 (2016) 91–95.
- [20] S. Salzer, et al., Noise limits in thin-film magnetolectric sensors with magnetic frequency conversion, *IEEE Sens. J.* 18 (2018) 596–604.
- [21] V. Annappureddy, et al., A $pT/\sqrt{\text{Hz}}$ sensitivity ac magnetic field sensor based on magnetolectric composites using low-loss piezoelectric single crystals, *Sens. Actuators A Phys.* 260 (2017) 206–211.
- [22] Z. Chu, X. Gao, W. Shi, P. MohammadJavad, S. Dong, A square-framed ME composite with inherent multiple resonant peaks for broadband magnetolectric response, *Sci. Bull. (Beijing)* 62 (2017) 1177–1180.
- [23] Y. Zhang, et al., Deterministic reversal of single magnetic vortex circulation by an electric field, *Sci. Bull. (Beijing)* 65 (2020) 1260–1267.
- [24] Z. Chu, M. PourhosseiniAsl, S. Dong, Review of multi-layered magnetolectric composite materials and devices applications, *J. Phys. D Appl. Phys.* 51 (2018), 243001.
- [25] Y. Wang, et al., An extremely low equivalent magnetic noise magnetolectric sensor, *Advanced Materilas* 23 (2011) 4111–4114.
- [26] C. Fang, et al., Significant reduction of equivalent magnetic noise by in-plane series connection in magnetolectric Metglas/Mn-doped Pb(Mg1/3Nb2/3)O3-PbTiO3 laminate composites, *J. Phys. D Appl. Phys.* 48 (2015), 465002.
- [27] Z. Chu, Z. Yu, M. PourhosseiniAsl, C. Tu, S. Dong, Enhanced low-frequency magnetic field sensitivity in magnetolectric composite with amplitude modulation method, *Appl. Phys. Lett.* 114 (2019), 132901.
- [28] Y.K. Fetisov, D.A. Burdin, D.V. Chashin, N.A. Ekonomov, High-sensitivity wideband magnetic field sensor using nonlinear resonance magnetolectric effect, *IEEE Sens. J.* 14 (2014) 2252–2256.
- [29] Z. Chu, et al., Enhanced resonance magnetolectric coupling in (1-1) connectivity composites, *Adv. Mater.* 29 (2017), 1606022.
- [30] J. Gao, et al., Equivalent magnetic noise analysis for a tunneling magneto-resistive magnetometer, *Ieee Electron Device Lett.* 41 (2020) 1400–1403.
- [31] Xa. Yuan, et al., Bobbin coil probe with sensor arrays for imaging and evaluation of longitudinal cracks inside aluminum tubes, *IEEE Sens. J.* 18 (2018) 6774–6781.
- [32] G.Y.T. Ali Sophiana, David Taylora, John Rudlin, Design of a pulsed eddy current sensor for detection of defects in aircraft lap-joints, *Sens. Actuators A Phys.* 101 (2002) 92.
- [33] T.R. Diogo, M. Caetano, Jorge Fernandes, Matthias Pelkner, Claude Fermon, Be.R.Susana Cardoso, Fernando Franco, Johannes Paul, Moisés Piedade, Paulo P. Freitas, High-resolution nondestructive test probes based on magneto-resistive sensors, *Ieee Trans. Ind. Electron.* 66 (2019) 7326.

Biographies

Zhaoqiang Chu received his Ph.D. degree in Advanced Materials and Mechanics from Peking University, Beijing, China, in 2020. He is currently an associate professor at College of Underwater Acoustic Engineering, Harbin Engineering University, China. His research interests focus on magnetolectric composites and device applications in sensing, energy and communication. He published over 27 peer-reviewed papers. He was invited as a reviewer for journals like *IEEE Transactions on Industrial Electronics*, *Applied Physics Letters*, *Journal of Physics D: Applied Physics*, *IEEE Transactions on Magnetics*, *IEEE Sensors Journal*, *Review of Scientific Instruments* etc. He can be reached by email at zhaoliangchu@hrbeu.edu.cn.

Zekun Jiang received the B.S. degree from the Underwater Acoustic Engineering College, Harbin Engineering University, China, in 2019, where he is currently pursuing the master's degree with the Acoustic Science and Technology Laboratory. His current research interests mainly focus on the signal processing of magnetic field detection.

Zhineng Mao received the B.A and M.S degree in Electronic and Communication Engineering, Harbin Institute of Technology and the Ph.D. in Information and Communication Engineering, Harbin Institute of Technology, 2020. He is now an assistant professor with Harbin Engineering University. His researches mainly focus on Magnetic anomaly detection and Magnetic induction communication.

Ying Shen was born in Jiangsu, China, in 1984. She received the B.S. degree in food science engineering from China Agricultural University, Beijing, China, in 2006, and the M.Sc. degree in biological system engineering and the Ph.D. degree in material science engineering from Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, in 2010 and 2014, respectively. From 2015–2017, she was a Senior Research Engineer with Multi-Dimension Technology Co., Ltd., where he was engaged in developing advanced TMR sensors. Her research was devoted to develop extreme sensitive and low noise TMR sensors with compact size in Weak Geomagnetic Field Monitoring. She is currently a Professor with Harbin Engineering University. Her research is mainly in the fields of magnetic anomaly detection, methods for target localization, and remote sensing and magnetometry.

Junqi Gao received the B.S. degree in materials science and engineering from Tsinghua University in 2008 and the Ph.D. degree in materials science and engineering from Virginia Tech in 2013. He was a Senior Engineer with the Bosch Research and Technology Center North America, where he worked on the development of high performance TMR magnetic sensors. He is currently a Professor with Harbin Engineering University. His researches mainly focus on design and application of magnetic sensors, energy harvesters, and nondestructive evaluation.

Shuxiang Dong is Professor of Materials Science & Engineering at College of Engineering, Peking University, China. Professor Dong holds MSc and Ph.D. degrees from Tsinghua University, China. Dr. Dong was a research associate at Materials Research

Institute, Pennsylvania State University, State College, PA, from Jan., 2000– Dec., 2001, and a research scientist and research professor at Materials Science & Authority Engineering, Virginia Tech, Blacksburg, VA, from Jan., 2002–May 2008. Professor Dong's research focuses on piezoelectric ceramics and magnetoelectric composite materials, piezoelectric actuators and micromotors, magnetic sensors, smart electronic devices, and their applications. He has authored over 160 peer-reviewed papers and 30 patents. Prof. Dong was chosen as Most Cited Chinese Researchers in 2014–2019, who were regarded as most influential scientists in the world by Elsevier.