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A Review on Non-destructive Evaluation of Civil Structures Using Magnetic Sensors

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Abstract. The growing demand towards life cycle sustainability has created a tremendous interest in non-destructive evaluation (NDE) to minimize manufacturing defects and waste, and to improve maintenance and extend service life. Applications of Magnetic Sensors (MSs) in NDE of civil engineering structures have become of great interest in recent years due to their non-contact data collection, and their high sensitivity under the influence of external stimuli such as strain, temperature, and humidity, to detect damage and deficiencies. There have been several advancements in MSs over the years for strain evaluation, corrosion monitoring, etc. based on the magnetic property changes. However, these MSs are at their nascent stages of development, and thus, there are several challenges that exist. This paper summarizes the recent advancements in MSs and their applications in civil engineering. Principle functions of different MSs are discussed, and their comparative characteristics are presented. The research challenges are highlighted and the roadmap towards high technology readiness level is discussed.

Keywords: Non-destructive evaluation · Magnetoresistve sensor · Eddy Current · Magnetic flux leakage · Hall effect sensor · Civil engineering

1 Introduction

Civil structures and infrastructures such as buildings, fuselage, wind turbines, tunnels, and bridges have a significant place within the economy and play an important role in facilitating standard of living for the world population. These structures are experiencing premature damage and can reach their end of life earlier than expected [1]. Replacing such structures is time-consuming, labor-intensive and costly, therefore, a variety of structural health monitoring (SHM) techniques have been used to evaluate the safety and structural integrity of these structures in order to reduce the financial losses, as well as health and safety issues [2]. SHM is a real-time monitoring method to reduce maintenance costs while improving reliability and safety, creating more sustainable infrastructures by providing effective maintenance and better resource allocation. Furthermore, it results in increasing service life and reducing the rate of consumption of resources and waste generation.

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Different SHM techniques have been used in civil applications, some examples are visual inspection, optical fiber sensing, resistance strain gages, piezoelectric transducers, vibration and modal analysis, and electric and electromagnetic techniques [3]. Despite all the advantages, SHM usage is limited in civil structures as it is costly, labor-intensive, and difficult to implement. The sensing equipment can be susceptible to failure under harsh environmental conditions, and installation of the systems with cabling and dedicated positions requires extensive time and labor efforts.

Innovative SHM methods are currently being investigated to overcome the technical challenges of conventional methods. Extensive research and progress have been made especially during the last decade on the use of magnetic sensors for SHM [4]. Magnetic sensors offer several advantages such as elevated sensitivity, reduced size and ability to perform as a self-powered sensor [5]. Though there are many types of magnetic sensors, the paper reviews the progress made on two popular off-the-shelf magnetic sensors, namely Hall Effect (HE) and Magnetoresistive (MR) sensors, for civil applications.

2 Fundamentals

Two common methods for magnetic-based damage detection are discussed in this section. HE and MR sensors are also described.

2.1 Magnetic Flux Leakage

A permanent magnet or an electromagnet in the form of a yoke can generate a nearly uniform magnetic field [6]. By placing a ferromagnetic object in the magnetic field, it can be magnetized and work as a magnet. When the object is cracked, the magnetic field leaks out. Because, compared to the healthy object, the air gap cannot support as much magnetic field per unit volume. The larger the flaw, the more the magnetic flux leakage (MFL). Putting a sensor near the damaged area, MFL and the damage can be identified. This mechanism is pictorially illustrated in Fig. 1.

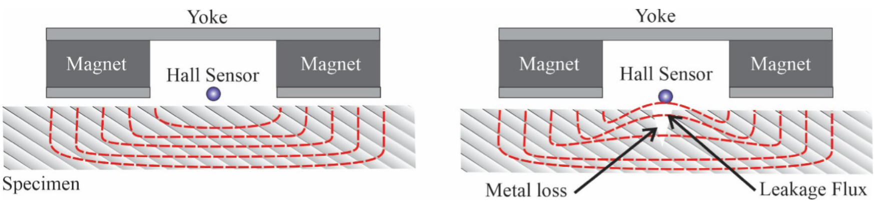

Fig. 1. A schematic of the MFL phenomenon.

2.2 Eddy Currents

Eddy Currents (ECs) occur when a conductor moves in a magnetic field, and the magnetic field around a fixed conductor is variable, or when there exists anything causing a change in the intensity or direction of a magnetic field in the conductor [7].

They circulate in the conductor like rotating vortices in closed loops perpendicular to the magnetic field plane (see Fig. 2).

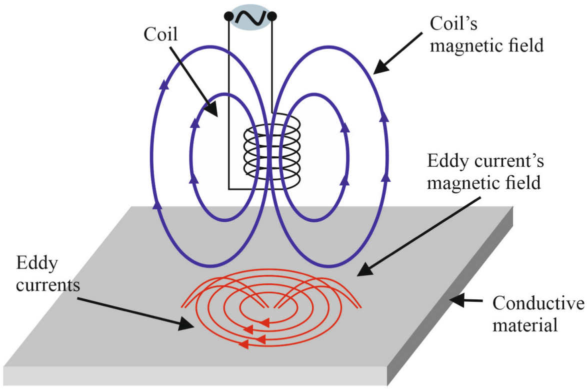

Fig. 2. Schematic of EC test.

When the current passes through the conductor, the EC creates a magnetic field. According to the lens law, the direction of the magnetically induced current will be such that the generated magnetic field opposes the change in the magnetic field creating it. This capability of ECs can be utilized to measure the health of conductive structures.

2.3 Hall Effect Sensors

According to the Hall Effect [8], when a current is applied to a thin strip of conductor in the presence of a magnetic field perpendicular to the direction of the current, the charge carriers are deflected by Lorentz force. Therefore, an electric potential difference is created between two sides of the strip, as shown in Fig. 3. The voltage difference (Hall voltage) is proportional to the strength of the magnetic field. The HE sensor detects the

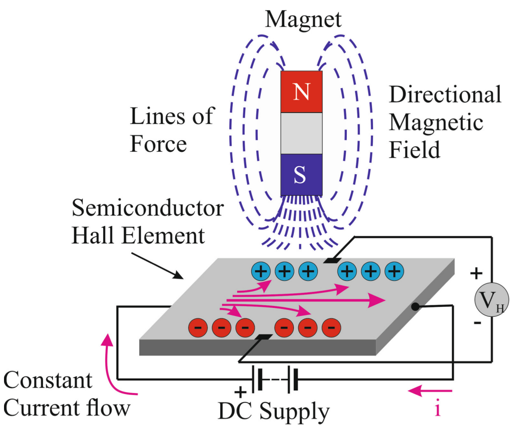

Fig. 3. The HE sensor working principle.

presence and magnitude of a magnetic field using the Hall Effect which makes them respond to fixed (non-changing) magnetic fields.

2.4 Magnetoresistive Sensors

Generally, there are three categories of MR sensors, namely anisotropic magnetoresistance (AMR), giant magnetoresistance (GMR) and tunneling magnetoresistance (TMR) sensors. The basic structure of each type of MR element is illustrated in Fig. 4.

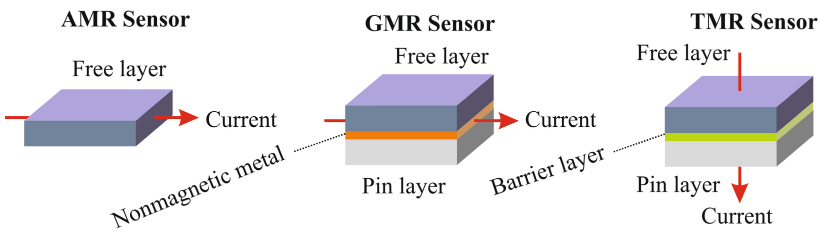

Fig. 4. Schematic diagram of AMR, GMR and TMR sensors.

The resistance in AMR sensors depends on the angle between the current and magnetization direction, where the resistance is in the smallest level at a vertical direction and in the highest level when the current is parallel [9]. GMRs feature up to 15% further magnetoresistance compared to AMR devices, and this is the reason for coining the prefix ‘giant’. GMRs have equal responses to positive or negative fields, but their sensitivity to perpendicular fields is small [9]. In TMR sensors, the electrical resistance becomes the smallest when the magnetization directions of the pin layer and free layer (shown in Fig. 4) are parallel, causing a large current to flow into the barrier layer [10].

3 Applications

Different applications of the HE and MR sensors in detecting damage in several types of structures are reviewed and discussed in the current section.

3.1 Hall Effect Sensors

Park *et al*. [11] proposed an inspection system to localize the damage in strands of cables, as shown in Fig. 5. They designed and manufactured an 8-channel MFL sensor equipped with one HE sensor installed in each channel. It was observed that the sensing varies with distance, thus a threshold based on generalized extreme value (GEV) distributions was determined to detect damage locations with a confidence level of 99.99%.

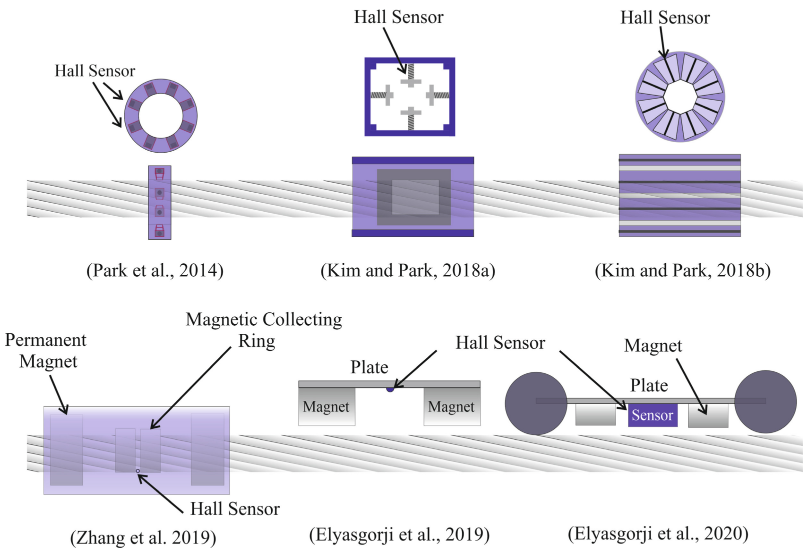

Fig. 5. Damage detection apparatuses based on magnetic flux leakage

Kim and Park [12] fabricated a sensor module including two pairs of yokes, made with high-strength Nd-Fe-B permanent magnets, carbon steel plates as magnetizers and HE sensors as signal measurement components. Moreover, to quantify the damage, they proposed three new indexes, namely peak value of envelope (E_p), the width of the envelope (E_w) and area of the envelope (E_A), and tested their sensitivity to width, depth and length of the damage. Compared with traditional peak-to-peak value (P-P_v) and peak-to-peak width (P-P_w) indexes, the proposed width and area of envelope indexes featured more reliability in quantifying damage severities. Further studies are required on various types of damage, such as corrosion and pressed damage for in-situ application of the method.

Zhang *et al.* [13] applied the circumferential multi-circuit permanent magnet exciter (CMPME), drawn in Fig. 5, to excite wire ropes more easily and uniformly. They optimized CMPME and inserted a magnetic concentrator, to increase the angular sensitivity range of HE sensors, reduce the number of sensors, and consequently simplify the signal processing. It was observed that after applying the wavelet transformation for denoising, the collected signals display a satisfactory sensitivity over external broken wires.

Elyasigorji *et al.* [14] fabricated an MFL apparatus with two DC permanent magnets connected with a steel plate and placed an HE sensor between the magnets, as seen in Fig. 5. They examined seven-wire strands with different section losses and gap lengths. It was demonstrated that peak to peak index and duration index respectively increase when loss percentage is increased.

Elyasgorji *et al.* [15] extended the previous research [14] and considered the effects of steel shear reinforcement (stirrups) using the device shown in Fig. 5. An apparatus consisting of two DC permanent magnets, 64 axial longitudinal and vertical HE sensors, was passed along the length of the strands. They utilized correlation analysis to identify the location of stirrups, and then their effects were removed from the measured signals to discover damage locations.

Fernandes et al. [16] investigated the detection of corrosion or fracture in prestressed strands in concrete structures. MFL-MMF magnetic techniques were used to compare and evaluate information to obtain comprehensive results for the test sample. HE sensors were used to detect leaky and original magnetic fluxes, which can greatly increase the accuracy of the measurements.

Zhang et al. [17] developed a method for detecting and measuring the amount of corrosion in reinforced concrete. In this method, a permanent magnetic source and an HE sensor are used, which can be embedded in concrete. The operating principles of this method are based on changing the magnetic permeability (MP) of steel rebars due to corrosion. According to experiments and results, as the amount of corrosion increases, the output voltage of the HE sensor increases with a linear relationship.

Alonso et al. [18] developed a method to measure the stress on magnetic steels. They created a magnetic field using a simple magnetic structure and measured this magnetic field with an HE sensor. It was observed that the amount of stress applied to the steel can change the amount of its MP.

Zhan et al. [19] presented a method for measuring the amount of cage slip in bearings. In this method, considering that the rollers inside the bearing can change the magnetic permeability (MP) of the body, using a magnetic sensor and an HE sensor, the position of the raceway and its slip relative to the loads was identified.

Park et al. [20] developed a pulsed EC sensor to measure the wall thickness of steel pipes. One of the advantages of this application is that there is no need to remove the pipe's cover, and the thickness can be measured from a distance of 6 mm. The structure of this sensor consists of a coil with a ferrite core as a magnetic field exciter and an HE sensor in the center of the coil. According to the measurement results, it is observed that the output signal of the sensor changes with the change of the pipe wall thickness.

3.2 Magnetoresistive Sensors

Wincheski et al. [21] developed a self-nulling probe device for the inspection of deep flaws. They used GMR sensors for their ease of use, favorable environment performance, lower power consumption, high sensitivity and small size. Finite element analysis showed that the device provides sufficient depth of penetration.

Chady [22] used GMR sensors for stress assessment in steel samples. He defined three straightforward indexes based on the voltage signal from the sensors. The measuring time for scanning an area of 41 cm^2 was about 10 min which can be reduced by using an array of sensors.

Popovics et al. [23] applied GMR sensors for corrosion sensing in concrete structures. They showed that corroding steel bars exhibit higher levels of magnetic noise as well as higher field gradient. It was shown that the residual magnetic field in bars can induce similar signals as corroded bars.

Procházka and Vaněk [24] studied blade damage identification through the tip-timing technique which is based on the time difference of blade passages. To extract the time differences, they used MR sensors that detect the blades made with ferromagnetic material and studied the amplitudes and time differences of generated impulse signals. It was shown that the amplitudes depend on the radial distance between the blade and the sensor, whereas the passage time of the output voltage through zero is independent of the distance. This method can be applied even in supersonic tip speeds up to 700 m/s because of the high sensitivity of the sensors.

Yang et al. [25] proposed a rotating electromagnetic field to detect cracks in all radial directions. They utilized two unidirectional coils oriented in orthogonal directions that outperform the traditional unidirectional coils. A GMR sensor was applied to measure the flux density of the induced field. The satisfactory performance of the new system was demonstrated through laboratory experiments as well as finite element simulation.

Tsukada et al. [26] developed a magnetic measuring system for detecting steel plate thickness and inner corrosions. The system includes an induction coil for applying an AC magnetic field to the plate and an AMR sensor for detecting the normal magnetic component. To increase signal to noise ratio (SNR), a cancellation coil was employed with the same phase of the induction coil. It was shown that the phase spectrum extracted from the magnetic spectrum is a reliable feature for thickness detection.

Tsukada et al. [27] presented an MFL method for analyzing the inner cracks in steels. The measurement device includes a semicircular yoke with induction coils at both ends, and a gradiometer having two AMR sensors between the two ends of the yoke. They observed that the intensity and phase change at the crack positions. It was shown that high frequencies are preferable for the detection of surface cracks, and low frequencies are desirable for deep ones.

Wincheski and Simpson [28] integrated MR sensors with EC probes. They designed a new EC probe incorporating a dual induction source that can be operated for deep flaw detection with low-frequency EC, and near-surface material characterizations with high resolution with high frequency EC.

Wincheski et al. [29] presented a probe including two orthogonal AMR sensors with in-plane placement and a single-strand conductor for induction of EC. This placement improves the SNR. In order to increase the scanning speed, a high-speed data acquisition system was employed. Finite element modeling and experimental results verified the quality performance of the probe.

Tsukada *et al.* [30, 31] designed a crack detection sensor in ferromagnetic materials using the EC method. They used TMR sensors and were able to achieve linear and 2D scan of surface cracks. The advantage of this method compared to classical sensors is that the magnetic field of the excitation coil does not affect the crack detection signal.

4 Discussion and Conclusions

In the present paper, the applications of magnetic sensors – particularly HE as well as MR sensors – in SHM are overviewed. Their low power consumption, high sensitivity and small size provide opportunities for green and sustainable sensing and pave the way for IoT and smart structures.

Because of the penetration capability of the magnetic field, inner damages and corrosions can be identified by this type of sensor which is a key advantage compared to vision-based techniques. It can be said that MSs perfectly complement the common SHM and NDT methods in the market.

HE sensors are cost-effective and can measure magnetic fields perpendicular to the sensor. On the other hand, MR sensors are rather expensive. They can provide an SNR at least 10 times higher than that of HE sensors, as well as a 100-times higher field resolution. The choice between these sensors is dependent on the required performance. Enhanced accuracy and reliability can be obtained through their combination, which is almost neglected in the literature.

Although this sensing technology in recent years received remarkable attention from the civil engineering community, there is still room for improvement. In the following, several challenges and prospects in this field are presented, upon which further studies and developments can be planned:

- A magnetic shock can affect the output of some MSs by an offset. Although it can be remedied through periodic magnetization, strong pulses should be avoided during instalment and application of the sensors.
- Fluxgates and MR sensors are prone to the Crossfield effect arising from magnetic fields perpendicular to the sensing direction – e.g., Earth's field. This issue can be addressed by feedback-compensated signal processing and magnetic anisotropy.
- Environment temperature can influence the signals and performance of the MSs. In this regard, temperature sensors and experimental results can be involved in the process to compensate for this effect.
- The magnetic fields exhibit sensitivity to element coating and geometry – e.g., thickness and element edge – which requires position-dependent calibration.
- The loading history of materials can alter some of their magnetic properties, such as residual magnetic field, without occurring any damage. This shows the necessity of proper techniques and feature selection for specific applications. The same goes for the material type of test structures.
- Most studies are just concentrated on the detection of damage presence or damage location. Various numerical, statistical and computational models can be developed to map the acquired signals to higher levels of SHM, such as the quantification of damage severity and damage prognosis.
- The magnetic sensors can be embedded in structures as contactless or inner permanent sensors. To resolve the power supply issue of this kind of implementation, high-performance nanogenerators and wireless power transmission techniques can be employed.
- Dynamic MSs are usually designed and tested for speeds lower than 1m/s. Developing high-speed scanning sensors is highly demanded.

References

1. Balageas, D., Fritzen, C.-P., Güemes, A.: Structural Health Monitoring, vol. 90. Wiley, Hoboken (2010)
2. Karballaeezadeh, N., Mohammadzadeh, D.S., Shamshirband, S., Hajikhodaverdikhan, P., Mosavi, A., Chau, K.-W.: Prediction of remaining service life of pavement using an optimized support vector machine (case study of Semnan-Firuzkuh road). Eng. Appl. Comput. Fluid Mech. **13**, 188–198 (2019)
3. Doebling, S.W., Farrar, C.R., Prime, M.B., Shevitz, D.W.: Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review (1996)
4. Draganová, K., Blažek, J., Praslička, D., Kmec, F.: Possibile applications of magnetic Microwires in aviation. Fatigue Aircr. Struct. (2013)
5. Marín, P.: Wireless stress sensor based on magnetic microwires. Magn. Sens.—Develop. Trends Appl. (2017)
6. Mandal, K., Atherton, D.L.: A study of magnetic flux-leakage signals. J. Phys. D Appl. Phys. **31**, 3211–3217 (1998)
7. Auld, B.A., Moulder, J.C.: Review of advances in quantitative eddy current nondestructive evaluation. J. Nondestr. Eval. **18**, 3–36 (1999). https://doi.org/10.1023/A:1021898520626
8. Hall, E.H.: On a new action of the magnet on electric currents1. Nature **21**, 361–361 (1880)
9. Jander, A., Smith, C., Schneider, R.: Magnetoresistive Sensors for Nondestructive Evaluation, vol. 5770. SPIE (2005)
10. Kumar, A.S.A., George, B., Mukhopadhyay, S.C.: Technologies and applications of angle sensors: a review. IEEE Sens. J. **21**, 7195–7206 (2021)
11. Park, S., Kim, J.-W., Lee, C., Lee, J.-J.: Magnetic flux leakage sensing-based steel cable NDE technique. Shock. Vib. **2014**, 929341 (2014)
12. Kim, J.-W., Park, S.: Magnetic flux leakage–based local damage detection and quantification for steel wire rope non-destructive evaluation. J. Intell. Mater. Syst. Struct. **29**, 3396–3410 (2018)
13. Zhang, Y., Jing, L., Xu, W., Zhan, W., Tan, J.: A sensor for broken wire detection of steel wire ropes based on the magnetic concentrating principle. Sensors **19**, 3763 (2019)
14. Elyasigorji, A., Rezaee, M., Ghorbanpoor, A.: Magnetic corrosion detection in concrete structures. In: International Conference on Sustainable Infrastructure 2019, pp. 175–184 (2019)
15. Elyasigorji, A., Rezaee, M., Ghorbanpoor, A.: Characterization of corrosion in PS concrete girders by correlation analysis. In: Structures Congress 2020, pp. 285–292 (2020)
16. Fernandes, B., Nims, D., Devabhaktuni, V.: Comprehensive MMF–MFL inspection for corrosion detection and estimation in embedded prestressing strands. J. Civ. Struct. Heal. Monit. **4**(1), 43–55 (2013). https://doi.org/10.1007/s13349-013-0061-4
17. Zhang, J., Liu, C., Sun, M., Li, Z.: An innovative corrosion evaluation technique for reinforced concrete structures using magnetic sensors. Constr. Build. Mater. **135**, 68–75 (2017)
18. Alonso, M.S.G., et al.: Magnetostatic determination of variations of internal stress in magnetic steels. AIP Adv. **10**, 115302 (2020)
19. Zhan, L., Ma, F., Li, Z., Li, H., Li, C.: Study on the cage slip of rolling bearing using a non-contact method. Struct. Health Monit. **19**, 2107–2121 (2020)
20. Park, D.G., Angani, C.S., Kim, G.D., Kim, C.G., Cheong, Y.M.: Evaluation of pulsed eddy current response and detection of the thickness variation in the stainless steel. IEEE Trans. Magn. **45**, 3893–3896 (2009)

21. Wincheski, B., Simpson, J., Namkung, M., Perey, D., Scales, E., Louie, R.: Development of giant Magnetoresistive inspection system for detection of deep fatigue cracks under airframe fasteners. In: AIP Conference Proceedings, vol. 615, pp. 1007–1014 (2002)
22. Chady, T.: Evaluation of stress loaded steel samples using GMR magnetic field sensor. IEEE Sens. J. **2**, 488–493 (2002)
23. Popovics, J., Gallo, G., Shelton, M., Chapman, P.: A magnetic sensing approach to characterize corrosion in reinforced concrete, vol. 6529. SPIE (2007)
24. Procházka, P., Vaněk, F.: Contactless diagnostics of turbine blade vibration and damage. J. Phys: Conf. Ser. **305**, 012116 (2011)
25. Yang, G., Dib, G., Udpa, L., Tamburrino, A., Udpa, S.S.: Rotating field EC-GMR sensor for crack detection at fastener site in layered structures. IEEE Sens. J. **15**, 463–470 (2015)
26. Tsukada, K., et al.: Detection of inner corrosion of steel construction using magnetic resistance sensor and magnetic spectroscopy analysis. IEEE Trans. Magn. **52**, 1–4 (2016)
27. Tsukada, K., et al.: Detection of inner cracks in thick steel plates using unsaturated AC magnetic flux leakage testing with a magnetic resistance gradiometer. IEEE Trans. Magn. **53**, 1–5 (2017)
28. Wincheski, B., Simpson, J.: Development and application of wide bandwidth magneto-resistive sensor based eddy current probe. In: AIP Conference Proceedings, vol. 1335, pp. 388–395 (2011)
29. Wincheski, B., Simpson, J., Seebo, J.P., Powell, J.: High-resolution imaging with two-axis orthogonal magneto-resistive sensor based eddy current probe. In: AIP Conference Proceedings, vol. 1430, pp. 366–372 (2012)
30. Tsukada, K., Hayashi, M., Nakamura, Y., Sakai, K., Kiwa, T.: Small eddy current testing sensor probe using a Tunneling Magnetoresistance sensor to detect cracks in steel structures. IEEE Trans. Magn. **54**, 1–5 (2018)
31. Hayashi, M., et al.: Extraction method of crack signal for inspection of complicated steel structures using a dual-channel magnetic sensor. Sensors **19**, 3001 (2019)