

# Magnetic field gradient as the most useful signal for detection of flaws using MFL technique

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The magnetic flux leakage (MFL) technique is extensively used for detection of flaws as well as for evaluation of their dimensions in ferromagnetic materials. However, proper analysis of the MFL signal is hindered by the MFL sensor velocity causing distortions of this signal. Traditionally measured components of the MFL signal are particularly sensitive to the scanning velocity. In this paper, another signal – the gradient of the normal component of magnetic flux density – was proposed as it is less sensitive to the scanning velocity. Results obtained for scans of the steel plate with artificially manufactured flaws confirm this statement.

**Keywords:** gradient of magnetic field, magnetic flux leakage, velocity-induced eddy currents

## 1 Introduction

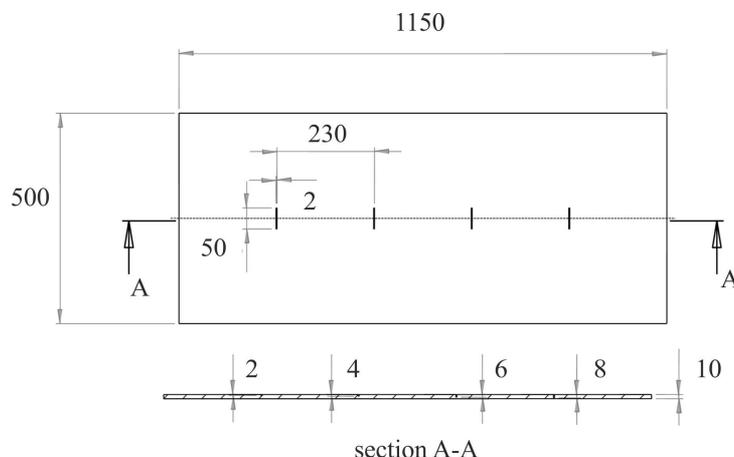
MFL technique is a non-destructive testing method commonly used for finding flaws *eg* metal losses caused by corrosion in steel constructions [1]. MFL method involves the use of a source of a strong magnetic flux, such as neodymium magnets, for magnetizing an object under investigation. The magnetic flux leaks from the object in the location of a flaw. Thus, the flaw can be detected by an MFL tool equipped with magnetic field sensors. Most MFL tools measure one or more components of magnetic flux density  $\mathbf{B}$ . With respect to the scanned surface and the direction of scanning one can define three components of  $\mathbf{B}$ : tangential ( $B_x$ ), transverse ( $B_y$ ), and normal ( $B_z$ ). Parameters such as a magnitude and a spatial distribution of these components depend on a shape of the flaw. Therefore, these components can be used to detect flaws as well as to evaluate their dimensions.

It has been reported that signals obtained for the aforementioned components are distorted by the scanning

velocity [2–4]. As a result, an estimation of flaw dimensions is less accurate. This issue is crucial in the case of the pipeline in-line inspection, where the scanning velocity is out of control. Different methods can be undertaken to deal with MFL signal distortions caused by the velocity. Most of them are based on a proper signal processing leading to restoration of the static form of the signal [4–6]. Other method assumes optimization of an MFL tool design in order to minimize the velocity impact [3]. In this work, another approach was proposed. This approach is based on the measurement of an additional quantity that is less vulnerable to the velocity impact. The gradient of the normal component measured along the scanning direction ( $\partial B_z / \partial x$ ) was proposed as a complementary signal component.

## 2 Experimental details

The experiment was carried out for a plate made of 18G2A (S355) steel grade. Four artificial flaws were milled



**Fig. 1.** The steel plate with artificially manufactured flaws in the form of a rectangular slot

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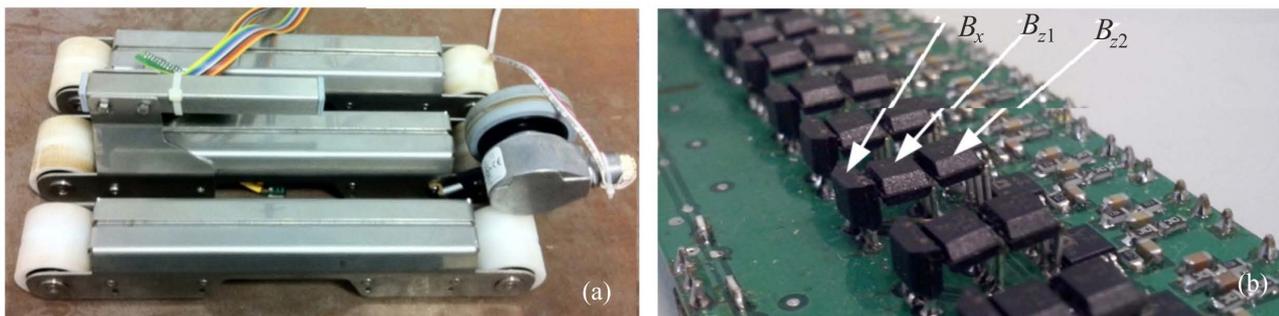


Fig. 2. (a) the MFL tool and (b) an array of hall effect sensors designed for scanning the defected surface of the steel plate

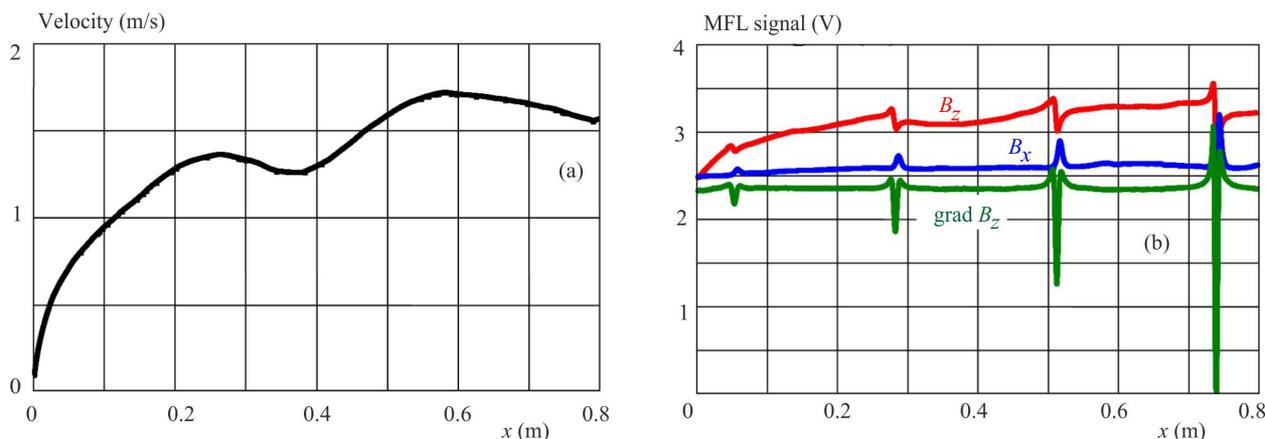


Fig. 3. Results of a steel plate scanning for the channel closest to the centre of flaws. (a) – velocity dependence on displacement of the MFL tool and (b) – waveforms of components of the MFL signal

on one of plate surfaces. Each flaw had a different depth. Dimensions of the plate and the flaws are presented in Fig. 1.

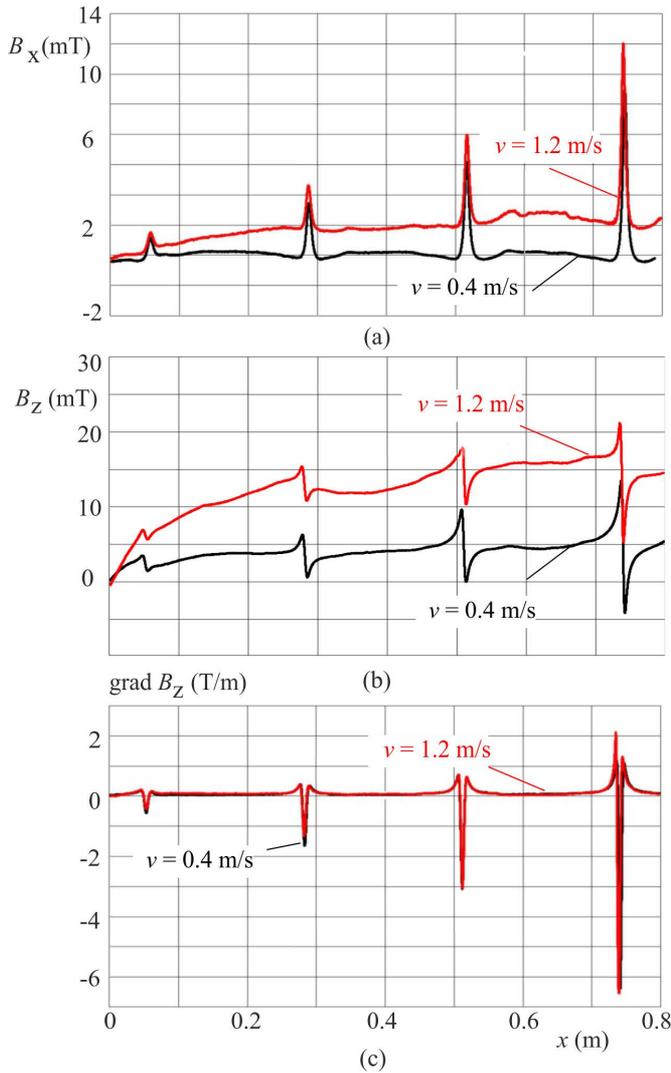
Figure 2(a) presents the MFL tool used in the experiment which was comprised of three magnetizers with two wheels each, a digital encoder, and a measurement module. Each magnetizer consisted of two neodymium magnets connected by a steel beam and was a source of the magnetic flux that magnetized the plate. The digital encoder provided information about the displacement of the MFL tool, and thus also about its velocity. The measurement module was comprised of ten units, each containing three linear Hall effect sensors A1324, as shown in Fig. 2(b). Each channel measured three voltage signals:  $B_x$  sensor output,  $B_{z1}$  sensor output, difference of  $B_{z2}$  and  $B_{z1}$  outputs.

### 3 Results

The velocity of the MFL tool, as a function of its displacement, and the corresponding MFL signal are presented in Fig. 3. The velocity was not constant during the measurement, as can be seen in Fig. 3(a). Waveforms of three measured components of the MFL signal are placed together in Fig. 3(b). Spikes that are visible on all the waveforms are characteristic features of the MFL signal. These spikes indicate locations of flaws in the investigated

steel plate. They also can be used for evaluation of flaw dimensions *ie* for the quantitative analysis. Accuracy of the quantitative evaluation is strongly dependent on shape distortions of a signal portion measured in the vicinity of a flaw. In the case under consideration, waveforms of all three components of the MFL signal are affected by the variable velocity. However, the velocity impact varies between the components. Based on the results presented in Fig. 3(b) one can state that  $B_z$  is the most dependent on velocity. The shape of the baseline of  $B_z$  is very similar to the shape of the velocity curve. Therefore, one can state that the baseline of  $B_z$  is proportional to the velocity.

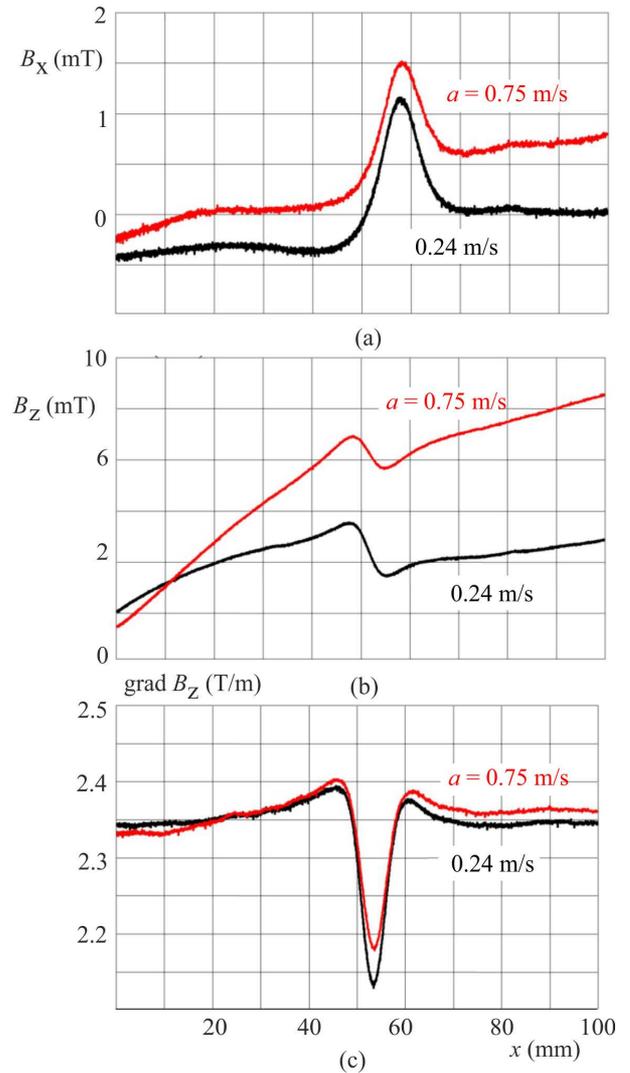
Waveforms of the particular signal components for two average velocities are presented separately in Fig. 4 due to a different velocity impact on each of them. Values of the signal components are expressed in their physical units. The faster measurement (1.2 m/s) corresponds to the results shown in Fig. 3. A comparison of two waveforms presented in Fig. 4(a) leads to the conclusion that  $B_x$ , similarly to  $B_z$ , changes proportionally to the velocity, although the offset of  $B_x$  caused by the velocity is lower than for  $B_z$ . Results for  $B_z$  presented in Fig. 4(b) confirm that this component is the most dependent on the velocity. Figure 4(c) shows that the gradient of  $B_z$  is much less affected by the velocity as compared to the other two measured signal components, as waveforms of  $\partial B_z / \partial x$  for two compared measurements are very close to each other.



**Fig. 4.** Comparison of waveforms for (a) – the tangential component, (b) – the normal component, and (c) – the gradient obtained for different values of average velocity of the MFL tool

As the MFL signal is velocity-dependent, also a non-zero acceleration can significantly influence waveforms of the signal components. During a single measurement the velocity of the MFL tool was initially ramped to a target value. As a consequence, the initial stage of a measurement was accompanied by a significant acceleration. Taking advantage of this fact, Fig. 5 shows the initial portion of the signal presented in Fig. 4, which are associated with the shallowest flaw. Two presented measurements differ in average value of the acceleration.

As can be seen in Fig. 5(a), the waveform of  $B_x$  corresponding to  $a = 0.75 \text{ m/s}^2$  has the higher velocity-related offset and the higher slope of the baseline than the waveform corresponding to  $a = 0.24 \text{ m/s}^2$ . Figure 5(b) shows that the effect of an additional linear contribution to a signal is even more clear for  $B_z$ . In the case of a non-zero acceleration, the waveform of  $\partial B_z / \partial x$  is distorted as well, but only slightly, as can be seen in Fig. 5(c). The waveform corresponding to  $a = 0.75 \text{ m/s}^2$  has the off-



**Fig. 5.** Comparison of waveforms for (a) – the tangential component, (b) – the normal component, and (c) – the gradient obtained for different values of acceleration of the MFL tool. Portions of the signals obtained in the vicinity of the 2 mm deep flaw are presented

set with respect to the waveform which corresponds to  $a = 0.24 \text{ m/s}^2$ . These results confirm observation about linear contribution to  $B_z$  for nearly constant acceleration. Due to derivation this contribution is transformed to an offset of  $\partial B_z / \partial x$ , what is corroborated by results presented in Fig. 5(c).

#### 4 Discussion

Based on the presented results, one can observe that waveforms of  $B_x$  and  $B_z$  are velocity dependent. A result of a non-zero velocity is an offset of these two signal components. This effect is around five times stronger for  $B_z$  than for  $B_x$ . Observed offsets indicate that there is a change in the magnetic field distribution above the surface of the sample, which means that a change of sample magnetization occurs during a measurement. Changes of the both magnetic induction components are proportional to the scanning velocity. Responsible for this effect is the

velocity-induced eddy current that exists under poles of a magnetizer yoke [2, 4, 7]. This eddy current, according to Faraday law of induction, is directly proportional to the relative velocity of the yoke with respect to the sample. The MFL signal can be distorted also by the eddy current induced in the vicinity of a flaw [8]. This type of the eddy current was not considered in presented analysis, but this issue will be a part of future works.

In a more complex case, where the scanning velocity is not constant, distortions of waveform shapes occur. It is significant problem from the point of view of the signal quantitative analysis. Among all measured MFL components, the gradient  $\partial B_z/\partial x$  is the least susceptible to a non-zero acceleration of the MFL tool. In the case of  $\partial B_z/\partial x$  a constant acceleration results in a DC offset proportional to this acceleration. However, the acceleration effect on  $\partial B_z/\partial x$  is weaker than the velocity effect on  $B_x$  and  $B_z$ , as can be deduced from Fig. 5.

## 5 Conclusion

A non-zero constant velocity of the MFL tool results in a DC offset of the tangential ( $B_x$ ) as well as the normal ( $B_z$ ) component of the MFL signal. This can lead to a situation in which peaks may extend beyond the signal operating range. In contrast to the aforementioned signal components, the gradient of the normal component ( $\partial B_z/\partial x$ ) does not exhibit such a property, which makes the gradient most promising candidate for quantitative analysis of the MFL signal. Future works will focus on the influence of the velocity and the acceleration on evaluation of flaw dimensions, taking into account three signal components presented in this work.

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## REFERENCES

- [1] P. C. Porter, "Use of Magnetic Flux Leakage (MFL) for the Inspection of Pipelines and Storage Tanks", *Proc. SPIE 2454*, Non-destructive Evaluation of Aging Utilities (1995), pp. 172–184.
- [2] Z. Gan and X. Chai, "Numerical Simulation on Magnetic Flux Leakage Testing of the Steel Cable at Different Speed Title", *ICEOE 2011 - International Conference on Electronics and Optoelectronics*, Proceedings, 2011, vol. 3, pp. 316–319.
- [3] L. Zhang, F. Belblidia, I. Cameron, J. Sienz, M. Boat and N. Pearson, "Influence of Specimen Velocity on the Leakage Signal Magnetic Flux Leakage Type Nondestructive Testing", *J. Nondestruct. Eval.* vol 34, no 6, 2015.
- [4] G. S. Park and S. H. Park, "Analysis of the Velocity-Induced Eddy Current MFL Type NDT", *IEEE Trans. Magn.*, vol. 40, no. 2, pp. 663–666, 2004.
- [5] L. Lei, C. Wang, F. Ji and Q. Wang, "RBF-Based Compensation of Velocity Effects on MFL Signals", *Insight-Non-Destructive Test. Cond. Monit.*, vol. 51, no. 9, pp. 508–511, 2009.
- [6] S. Mandayam, L. Udpa, S. S. Udpa and W. Lord, "Invariance Transformations for Magnetic Flux Leakage Signals", *IEEE Trans. Magn.* vol. 32, pp. 1577–1580, 1996.
- [7] J. B. Nestleroth and R. J. Davis, "The Effects of Magnetizer Velocity on Magnetic Flux Leakage Signals", *Review of Progress Quantitative Nondestructive Evaluation* vol. 12A and 12B, D. O. Thompson and D. E. Chimenti (editors), Boston, MA: Springer US, 1993, pp. 1891–1898.
- [8] G. Katragadda, Y. S. Sun, W. Lord, S. S. Udpa and L. Udpa, "Velocity Effects and their Minimization MFL Inspection of Pipelines – a Numerical Study", *Review of Progress Quantitative Nondestructive Evaluation*, vol. 14, D. O. Thompson and D. E. Chimenti (editors), New York: Plenum Press, 1995, pp. 499–505.

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