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Comparative Study of three non-destructive techniques for metal loss inspection in pipe walls

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Abstract. Identifying and describing metal loss defects in pipe walls is an indispensable task in transporting operations, this abnormal condition mainly appears as a result of corrosion and gouging. These metal losses can lead the pipeline to unsafe conditions originating leaks, rupture of the structure and associated hazards. In this work is presented a comparative study to assess the capabilities of detecting and describing the metal loss in a pipe wall based on three non-destructive techniques: Magnetic Flux Leakage, Eddy Current Testing, and Guided Waves. These are compared by revising their physical principle and presenting a brief review of results obtained in metal loss inspection by considering some criteria as its sensitivity, depth of penetration, the range of inspection, and implementation easiness. Finally, the discussion is focused on of establishing which technique is most adequate for the inspection according to some characteristics of the metal loss defect.

1. Introduction

Magnetic Flux Leakage, Guided Waves, and Eddy Current testing are the most common on Non-destructive techniques used in the pipeline industry. These techniques have an advantage over others like liquid penetrant testing or X-ray as these allows automatic implementation and variations in designing for adapting to different conditions required.

A common characteristic of three techniques is that all of them can be generated by taking advantage of the properties of magnetic fields: One way of generating guided waves is by using magnetostriction principle, where the shape and size of ferromagnetic materials change during magnetization, eddy currents are produced due to the presence of a varying magnetic field in the test material and MFL take advantage of the leakage of the magnetic field around a metal loss defect.

This paper pretends to compare these three techniques in terms of detection and diagnosis capabilities and implementation in situ. The selected criteria to compare these techniques are based on determining high capabilities to detect and diagnose metal loss. The implementation easiness stands for the design and building of the transducer for the specific exploring condition excluding for the electronic components. The high sensitivity of the technique may produce false alarms and the relevant defects are not always the smaller ones. Therefore, a trade-off between high sensitivity and detection robustness must be considered.

2. Magnetic Flux Leakage

Magnetic Flux Leakage (MFL) is the most widely used method for inspecting cracks, corrosion and other associated defects in pipelines. MFL setup is composed by a ferromagnetic core with an energized coil or with strong permanent magnets like NdFeB to apply a magnetic field to the pipe wall close to saturation. The discontinuities presence in the pipe wall yields magnetic field leakage around the defect which is detected via an array of magnetic sensors. In this way, the screening is performed just in the pipe wall covered by the magnetic sensors. This technique provides information for characterizing the wall loss shape by estimating its width, length, and depth that are measured in the axial, circumferential and radial direction of the pipe [1]. These dimensions are estimated by analysing the signatures of MFL



signals that are composed of the three-axis components of the magnetic field flowing around of the discontinuity.

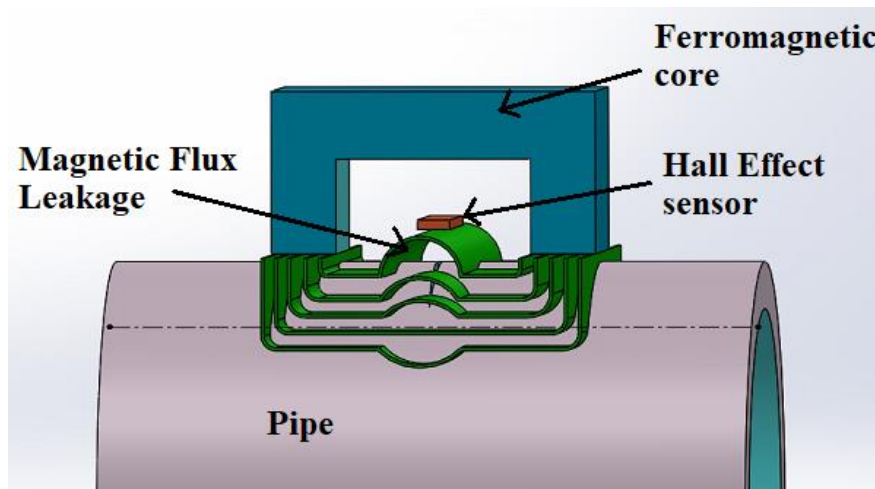


Figure 1. Principle of Magnetic Flux Leakage in a pipe with metal loss

Some features in the MFL signals are related to defect dimensions as criteria for estimating its shape. The length and width estimation of metal loss is highly affected by defect depth altering the accuracy of the estimated value of these magnitudes [2]. Some features of the selected signal as criteria are obtained experimentally [3], for example, a higher magnitude of MFL signals may be interpreted as large depths in metal loss defect [4], and also large discontinuity width. From the axial distance between intersection points of axial MFL signal is estimated the defect length and from the circumferential distance between the points where the axial signal has drop 70% of its peak value is estimated the defect width. Other criteria for estimating length and width are the peak values of radial and circumferential MFL signals [2]. Similar established criteria are proposed in other works [5]. Another challenge related to metal loss wall are the cracks with axial orientation and narrow widths that are typically almost undetectable as the magnetic field generated has the same orientation. One way of solving this difficulty is changing the direction of the magnetic field [3]. In [6] cracks of 50x5x2 mm are clearly detected. In [3] cracks of 0.1 mm with, 5% to 20% of wall thickness depth and 25 mm length were detected with high repeatability. When the magnetic field is generated in the ferromagnetic core by induction coils; the depth of penetration depends on frequency and material properties. In this case, depth of penetration is the same as Eddy current testing [7]. MFL based on permanent magnets are unable to provide the discontinuity depth of penetration as the technique covers the whole cross-section with different intensity.

On the other hand, the implementation of the MFL system requires to verify the saturation point in the magnetization curve of the material under exploration. This point provides the necessary information of the magnetic field that must be generated. This field is generated by the magnetic circuit composed of the ferromagnetic core, the pipe wall and the corresponding source that can be permanent magnets or induction coils [8]. The behavior of the magnetic field is described by Maxwell equations that are the base of the modeling software used for this technique.

For extracting information about detection, location or sizing of metal loss from the three MFL components, it has been applied several methods like pattern-adapted wavelets, Hilbert, Hilbert Huang Transforms, artificial neural networks [4]. In addition, this technique allows designing and modeling MFL sensing systems with different software such as “Ansys” [5], “Magnet” [9], “Gmsh”, “GetDP” [10] or “Comsol” [11], among others, applying criteria for designing the appropriate MFL sensor for the pipe.

3. Guided Waves

Guided waves are suitable for inspecting defects in pipes because of its capability for exploring long distance in the range of hundreds of meters from a single probe position [12]. This range is affected by

the operating frequency, pipe coating, insulation, depth of burial, among other factors. In contrast to ultrasonic bulk waves that usually propagates at frequencies in the order of MHz guided waves work typically between 20 and 200 KHz range [12]. For bulk waves, longitudinal and shear wave speeds in steel are 5.96 km/s and 3.26 km/s, respectively, for guided waves speed depends on frequency and mode excitation. Several type of guided waves can be generated depending on its boundary conditions, material properties, and geometry conditions: Rayleigh waves propagate along a single surface as rods and rail tracks; lamb waves propagate in solid plates and analogous to lamb waves are longitudinal, torsional and flexural waves that propagate in pipes or cylindrical structures. The behavior of guided waves in pipes can be modeled by the Navier's governing (1) wave equation with appropriate boundary conditions [13]

$$\mu \nabla^2 \bar{U} + (\lambda + \mu) \nabla \nabla \bar{U} = \rho (\partial^2 \bar{U} / \partial t^2) \quad (1)$$

Ultrasonic wave propagation without boundaries yields bulk waves instead of guided waves. By solving the equations according to a specific structure (thickness and material), it is obtained the dispersion curves. These curves show which modes can be generated in a hollow cylinder and at which velocity for a given spectrum frequency of a signal excitation. In figure 2 is presented the phase velocity dispersion curve for a one-inch steel pipe.

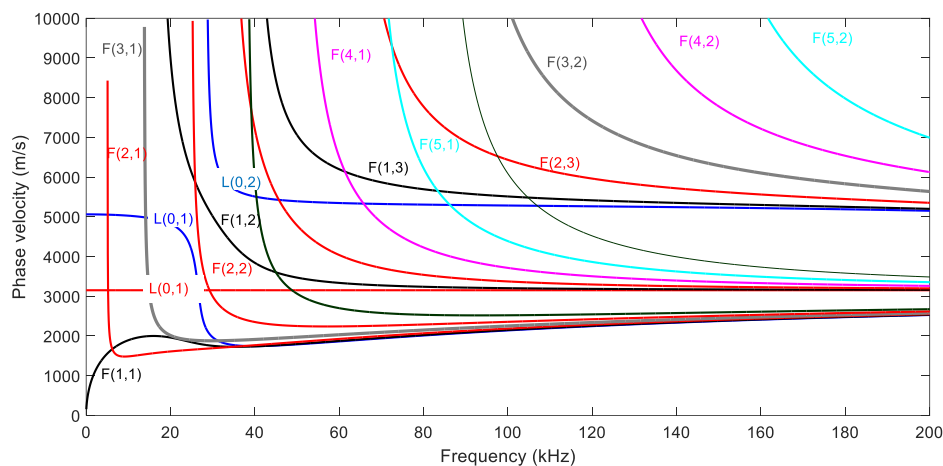


Figure 2. Phase speed dispersion curves for a 1" Sch. 40 A-106 pipe

A key element of the inspection is the selection of a single mode. Exciting several modes in the range of the bandwidth frequency of the excitation signal produce the propagation of a signal with multiple wavepackets which is much too complicated to interpret or analysis. One suitable mode is the first torsional mode $T(0,1)$, as it is nondispersive [14], it means the velocity is independent of frequency and it is not strongly affected by the fluid inside or outside of the pipe. The second longitudinal model $L(0,2)$ is also nondispersive in a long range of frequency and it is faster than many unwanted modes, so this mode is received before the unwanted signals arrive [15]. Flexural modes have been also used to indicate defects near or at a weld [16]. In addition to these ones, other modes have been used for inspecting purposes [16], [17].

High sensitivity to small discontinuities has been reported in some research works using guided waves. $T(0,1)$ were used to recognize a notch of 0.5 mm depth in a 1 mm wall thickness, while a shallower groove modeling surface corrosion of 0.3 mm depth was recognized by $L(0,1)$ mode [12]. Artificial notches of up to 5% of thickness wall were detected by $T(0,1)$ mode on a bent pipe [18]. The size of damage is also related to the time of flight and the instantaneous phase of the guided wave. The change in time of flight and phase of $L(0,1)$ was used to distinguish between pristine pipe and 1.6 mm damage diameter among others [19].

Implementing the guided wave hardware requires to know the waveguide material and dimensions to select the suitable modes to be used in the specimen assessment. According to the desired excitation mode array of transducers are located with specific space between them. These sensors are typically bonded to the pipe, so it has to consider the effects of the bonding layer in the received signal [19], [20], on the other hand, EMAT does not need any bonding couplant as the guided wave is generated through an alternating magnetic field [18], [16].

4. Eddy Current Testing

This method is based on the generation of an electric current induced on the test material due to an alternating magnetic field generated by a coil pointing to the material. This behaviour is described in Faraday's electromagnetic induction law. This induced current generates a secondary magnetic field that opposes the field that produced it. This technique has several configurations for sensing the secondary magnetic field. Some of them use a receiving coil to sense the magnetic field generated by the induced current. If the induced current is interrupted by the presence of a defect in the material, the receiving coil detect a variation in the magnetic field.

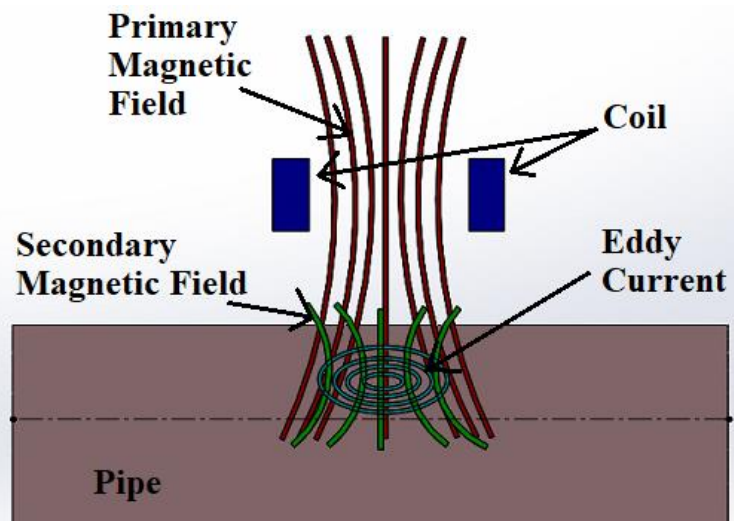


Figure 3. Primary and secondary magnetic field in pipe wall

The sensitivity of this technique is given by the size of the coils, its orientation, the electrical conductivity σ of the material to be inspected, the magnetic permeability μ and the excitation frequency. The depth of penetration affects the sensitivity of the instruments as the eddy current generated is denser near the surface of the test piece, where the probe is close. Eddy current decrease its density with the distance to the surface. In this way, a standard depth of penetration is defined where the instrument is sensitive to defects. Standard depth of penetration is described by equation (2), where the frequency, magnetic permeability and conductivity increase the depth of penetration decrease.

$$\delta = \sqrt{\frac{2}{\mu\omega\sigma}} \quad (2)$$

For a frequency of 250 KHz, using a stainless steel type 304 pipe, the standard depth penetration is 0.9 mm. [21]. The instrument sensitivity is also affected by the condition of the surface as porosity, or corrosion as these conditions have regions where no eddy current are able to flow giving false alarms. One way of improving the sensitivity of the technique is by working with pulsed eddy current instruments (PEC) [22] that generate square, triangular and other waveforms instead of single sinusoidal excitation. This improvement gives a broad spectrum of frequency that gives information about the characteristics of the hidden defects in the piece under investigation. Sensitivity is also affected by the

direction of the eddy current generated. If a metal loss depicted as a crack has the same orientation than eddy currents, the instruments are not able to detect them. For this reason, the exciting coils that draw the orientation of eddy current are designed forming spirals with different forms looking to detect different sizes and shapes of metal loss defects. Recent works showing the sensitivity of eddy current testing has given good results. Applying several novel configurations in the flexible exciting coils of eddy current probes is possible to detect artificial defects with 500 μm depth, 200 μm width and 2 to 4 mm length at a frequency of 200 KHz [23]. External corrosion with dimensions between 2 and 4 mm depth, 14 to 27 mm width, and 20 to 40 mm length were shaped using Pulsed Modulated Eddy Current (PMEC) and Pulsed Eddy Current (PEC) [24]

Table 1. Comparison of techniques.

	MFL	Guided Waves Testing	Eddy Current Testing
Sensitivity	High, but is still needs improving in quantifying and shaping defects	High	High,
Depth of penetration	High	High	Depends on frequency, conductivity and magnetic permeability of the material. It is often used to detect defects near the surface
Range of Inspection	In situ	Long Range	In Situ
Implementation easiness	High,	Medium. With some transducers material designing and configuration must be specific for generating the modes required	High

Conclusions

The three techniques revised have high sensitivity for small defects but results in quantification have better results in Guided Wave testing and Eddy Current testing than in Magnetic Flux Leakage due to the complex relationship between MFL signals and dimension of the metal loss. However, in guided waves reducing frequency will reduce the capacity of detecting defects. In eddy current testing the size and shape of the picking up coil must be designed according to the kind of defect that is forwarded to detect.

The whole penetration and screening in the wall thickness of the pipe can be achieved by magnetic flux leakage and guided waves when the system is properly configured, however the Eddy Current Technique is strongly affected by the frequency and it is not always covering the whole thickness.

Magnetic flux leakage and Eddy Current testing allow to design and implement the sensors in an easier way compared with guided waves implementation when the actuation and sensing are performed with piezoceramic sensors. Ferromagnetic cores with different dimension and coils of different shapes are more intuitive for designing and building than guided waves testing sensors. Guided Waves generation typically requires the configuration of more variables such as material, frequency, transducers arrangement, etc

If a long range is required in an inspecting procedure the best option is guided waves, although Eddy Current Testing and Magnetic Flux Leakage can be set up to cover long distances by displacing the system along the pipe. However, if it is required to move the instrument Guided Wave is not the best option as the transducers need to be strongly attached to the pipe.

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