NDT and E International 91 (2017) 148–155

Contents lists available at ScienceDirect

NDT and E International

journal homepage: www.elsevier.com/locate/ndteint

Composite magnetic flux leakage detection method for pipelines using alternating magnetic field excitation

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ARTICLE INFO

Keywords:
Magnetic flux leakage (MFL)
Axial magnetization
Circumferential eddy current
Induced magnetic field (IMF)
Pipeline
Missed detection

ABSTRACT

Pipelines are an important transportation medium for petroleum and chemical products, but defects in the pipelines can present hidden dangers and affect the safe operation of the pipeline. The traditional pipeline magnetic flux leakage (MFL) scanning technique generally adopts the axial magnetization mode, which has increased the difficulty in detection and the possibility of missed detection of axial cracks. In this paper, a new composite MFL method using alternating magnetic field excitation is proposed for the detection of cracks in pipelines. The alternating magnetic field is first superimposed on the MFL magnetization field, which will form a parallel eddy current field perpendicular to the magnetization direction in the pipeline wall. The defects in the pipeline not only cause the flux leakage of the magnetization field, but also lead to the disturbance of the circumferential eddy current field. The disturbance signals can be picked up through a secondary induced magnetic field. Because the magnetic field and the eddy current field are orthogonal, the presented method can implement synchronous detection in two orthogonal directions to avoid missed detection caused by the crack orientation. A series of physical experiments are carried out in this paper. The results show that two orthogonal detection signals can be separated by a simple low pass filter. Therefore, with only one scan, the new detector can obtain the defect characteristics in the axial and circumferential directions to overcome the blind spot problem seen in traditional MFL detectors.

1. Introduction

Pipelines[1] are commonly known as the great arteries of industrial systems, which play an important role in the development of the national economy. Pipeline transmission is widely used in many industrial sectors, such as nuclear power plants, petroleum, and gas. During pipeline service, defects caused by corrosion, internal stress, welding, slag inclusion, and other factors are considered the main cause of accidents [1]. These accidents threaten the safety of oil and gas transportation and personnel, and cause serious damage to the environment. Monitoring the health status of oil and gas pipelines in service, eliminating the hidden dangers caused by pipeline defects, and carrying out pipeline inspections on schedule has a very important engineering significance.

At present, the detection of corrosion defects in a long distance pipeline by using magnetic flux leakage (MFL) technology is a well-developed process and is widely used. However, due to the complexity of the crack shape and the particularity of its geometrical distribution, the result of applying the MFL technology to crack detection is not satisfactory. In the traditional MFL method, the distribution of the leakage magnetic field caused by cracks is closely related to the magnetization direction. Effective detection sensitivity can be achieved only when the detected crack is perpendicular to the magnetization direction of the MFL detector. When the crack direction is parallel to the magnetization direction, the flux leakage to the air is negligible. The phenomenon is bound to form a blind spot for the MFL detector, which increases the detection difficulty and the possibility of missed detection of cracks.

Many scholars have carried out relevant research and achieved certain results with the aim of improving the MFL technology. These studies have contributed to enhancing the detection accuracy of defects to a certain extent, but the discussion and research on the blind spot problem in crack detection is still relatively rare.

Some of the principle research on MFL detection, such as that performed by Yang L J and Zhang G G, adopted the ANSYS software to simulate the effect of lift-off on the MFL signal in non-destructive testing (NDT) of oil pipelines. The results of the research indicate that sensor lift-

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http://dx.doi.org/10.1016/j.ndteint.2017.07.002
Received 16 December 2016; Received in revised form 24 June 2017; Accepted 4 July 2017
Available online 16 July 2017

off has a substantially greater effect on the peak MFL amplitude than magnetizer lift-off of the same magnitude [2]. By using the 2D magnetic dipole theory, Liu B, Cao Y, and Zhang H modeled the magnetic leakage distribution from the linear defects of oil-gas pipelines in a weak magnetic field. The analysis results indicated that the radial signals of inside-outside defects could be clearly distinguished. The method is useful for the identification of defects located inside or outside the pipelines [3]. Song X C and Xue L studied the 3D finite element method (FEM) under mechanics-magnetic coupling, and simulated the relationship between MFL and loaded stresses for a crack. The conclusions are beneficial to the improvement of the post processing technique of MFL detection [4].

In terms of improving the performance of the MFL detector, Parra-Raad J A and Roa-Prada S made use of the forward analysis of the magnetic circuit to suggest a methodology for design optimization. The research can be used to reduce the design cost and improve the detection efficiency of the MFL inner detector [5]. Researchers such as Ma Y L and He R Y solved the problem of low signal to noise ratio (SNR) of the MFL detection signals by using a magnetic concentrating device. There search results indicate that the scan width increases when using a magnetic concentrating device, and correspondingly, the requirements of the lift-off value are reduced [6]. Gao T Y and Yu Y L focused on the interaction due to the introduction of multiple magnetic circuits in an MFL inspector. Magnetic intensity and permeability of the ferromagnetic materials along with the characteristics of signals generated by the defects were analyzed. This research has a certain reference value for optimizing the structure of MFL pipeline detectors [7]. Wang P, Gao Y L et al. analyzed the relationship between the speed of the MFL detectors and the magnetic field intensity near the cracks by means of the FEM. The limit speed of the MFL detector was determined to be about 200 km/h in the experiment. The results can provide an effective reference for the design of high-speed MFL detectors [8].

In terms of signal extraction and processing in MFL detection, Khodayari-Rostamabad A and Reilly J P put forward a complete machine learning procedure for the inspection of MFL images from pipelines. The average detection performance in recognizing major injurious metal defects versus non-injurious or benign anomalies was over 96% [9]. Saranya R, Daniel J, Abudhahir A et al. used the automatic segmentation technique to deal with the MFL images of the pipelines to obtain the crack information. They found that the region growing technique performed well for almost all MFL images [10]. Ravan M and Amineh R K proposed an inversion method for estimating the shape parameters of multiple cracks of arbitrary arrangements from the MFL signals. In the method, Canny edge detection and SM optimization were employed to simultaneously estimate the locations, orientations, lengths, and depths of the cracks [11].

Several scholars and researchers have carried out remarkable researches related to the detection of axially oriented cracks. Beissner R E, Teller C M, Burkhardt G L et al. analyzed the electric-current perturbation signals based on an analytic solution for the change in current density caused by a slot of infinite length and finite depth. The research offers the possibility of determining flaw characteristics through analysis of signal shapes and amplitudes [12]. Dover W D, Collins R and Michael D H compared the crack detection capability of alternating current potential difference (ACPD) and alternating current field measurement (ACFM). It was demonstrated that the ACFM provides accurate crack depth predictions for small deep cracks [13]. Kim D, Udpa L and Udpa S designed a detection mechanism for stress corrosion cracks by using multi-phase rotating magnetic fields. Experimental results show that this method is sensitive to axially oriented tight cracks [14]. Gao Y, Tian G Y and Wang P proposed electromagnetic pulsed thermography for defect characterization. The method is robust to lift-off changes and has invariant features for detection of various types of cracks [15].

A composite MFL detection method obtained by integrating with the ACFM technology is proposed with the aim of addressing the problem of missed detection of axial cracks in the existing MFL pipeline detector. By means of the superimposed alternating magnetic field, the proposed method forms an eddy current field, which is perpendicular to the magnetization direction in the pipeline wall. The disturbances in the eddy current field caused by the defects are reflected by the secondary magnetic field. The DC magnetization field and the AC eddy current field are associated with two different kinds of detection media, to avoid interference between them. Moreover, the detections of the two kinds of detection media are orthogonal to each other, so that the proposed method has the ability to detect cracks along two orthogonal directions simultaneously.

In signal processing, the MFL signals have DC characteristics, and the secondary magnetic fields induced by the eddy current field have AC characteristics. The two signals can be picked up by Hall sensors simultaneously, and are easily separated by a low pass filter. By superimposing an alternating magnetic field and introducing an orthogonal eddy current field, the presented method realizes composite detection of cracks with two kinds of media (i.e., electricity and magnetism). The method can obtain the defect information from two orthogonal detection directions to avoid the missed detection of axial cracks.

2. Analysis of missed detection of traditional MFL detectors

The rolling process, which is widely used in the manufacture of oil and gas pipelines, leads to a sharp increase in the residual stress of the steel plate. Therefore, the types of cracks that may form include hydrogen-induced cracks, fatigue cracks, and stress corrosion cracks. However, the axial stress corrosion crack along the longitudinal distribution of the pipeline is the most common type [16]. If not detected and eliminated in a timely manner, axial cracks may cause cracking in the pipe wall and lead to oil and gas leakage, thereby endangering the safety of people and property. Fig. 1 is a picture of a burst pipe due to axial crack propagation. Therefore, realizing the efficient detection of pipeline cracks is an issue that cannot be ignored, especially in the case of axial cracks.

However, several cases show that there are many missed detections when detecting the axial cracks in the magnetization direction used by the existing MFL detector. This phenomenon is a common problem in the field of pipeline detection, and a solution is urgently needed. In the study of the MFL technology, the smaller openings and lower flux leakage of cracks are generally thought to be the main cause of missed detections while using MFL detectors. However, we have found through onsite observations that the sensitivity of the MFL detectors to cracks is closely related to the crack orientation [17].

In the following analysis, we focus on the effect of crack orientation on the MFL detection signals. Suppose there is a crack of depth h, width $2w$, and length $2l$ on the surface of the tested pipeline, as shown in Fig. 2. When the pipeline is tested by an MFL detector, the standard axial magnetization mode is applied along the pipeline, wherein the magnetic flux density is B. For convenience, the crack center is set as the origin, the axial direction (magnetization direction) of the pipeline is set as the x axis, and the circumferential direction is set as the y axis. Further, the

Fig. 1. Burst failure caused by an axial crack in the operation of a pipeline.