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Tridimensional Magnetic Field Analysis for Pipeline Defect Inspection

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Abstract: Magnetic testing technique is generally considered to be an efficient and effective non-destructive testing (NDT) method and has been widely used in the ferromagnetic materials inspection industry. Interpreting magnetic signals and quantitatively evaluating flaw geometry constitute the overall goal of magnetic inspection procedure. In the geomagnetic field, high-pressure oil and gas pipeline has significant magneto-mechanical effect. Combined with high-accuracy magnetometer, stress concentrations caused by pipeline defects can be detected and then be analyzed. In this paper, a nonlinear structural finite element analysis (FEA) model is created for pipeline magnetic testing and the properties of three components of the magnetic field are investigated. According to numerical simulations, an increase in the magnetic peak-to-peak amplitude is observed with an increase in the pipeline pressure. The relationship between pipeline parameter and spontaneous magnetic flux leakage signals could be utilized in the magnetic testing technique to characterize the pipeline defects.

Keywords: finite element analysis, magneto-mechanical effect, magnetic testing, pipeline

1. Introduction

The application of non-destructive testing (NDT) is an integral part of oil and gas pipeline integrity management. Several NDT techniques are available for oil and gas pipeline inspection and magnetic testing technique is generally considered to be the most widely accepted and applied [1-3]. In the geomagnetic field, high-pressure oil and gas pipeline has significant magneto-mechanical effect, and stress concentration caused by pipeline defects can distort pipeline magnetic field on the ground [4]. By detecting magnetic anomalies signals using micro-magnetic sensor on the ground, defects and local stress concentrations of pipeline can be evaluated [1]. The principles of pipeline magnetic testing technique include the magneto-elastic effect, the magneto-plastic effect, the magnetic field leakage (MFL) effect and the spatial distribution of spontaneous magnetic flux leakage (SMFL). The magneto-elastic effect can be defined as the change in pipeline magnetization with stress in the geomagnetic field [5].The magneto-plastic effect, represented as an irreversible increase of the induced magnetic fields, is conditioned by the mechanical stress in the geomagnetic field [3].The MFL effect is caused by structural and mechanical inhomogeneities of the pipelines under the conditions of natural magnetization. Losses in the pipe wall thickness, perhaps caused by corrosion or cracks, results in a redistribution of the magnetic field in the vicinity of the flaw, causing some of the magnetic field to leak out [2]. The spatial distribution of SMFL is important for magnetic testing technology, especially in terms of the identification of pipeline defects.

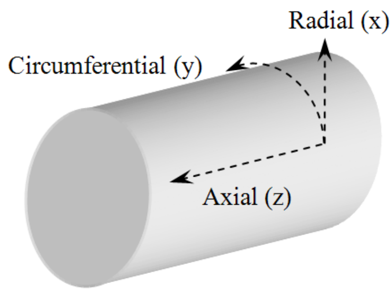


Fig. 1 Tridimensional pipeline cylindrical coordinate system

Detecting and characterizing defects constitutes the overall goal of the magnetic testing procedure. Defect detection using magnetic sensors is a mature area of work, but defect characterization using magnetic signals is an open research problem. Several issues involved in this process are not well understood, for example, the interplay of tridimensional SMFL field for tridimensional defects, the effect of pipeline pressure on magnetic signals, and the relationships between defect properties and magnetic signal properties. As indicated above, stress concentration and metal loss induce anomalous readings in the SMFL field, where field is a vector field. Applying a convenient cylindrical frame of reference, coinciding with the pipeline axis, the axial, radial and circumferential components of SMFL field are identified as shown in Fig. 1. In this paper, tridimensional finite element analysis (FEA) has been used to model SMFL field for the examination of pipelines. The properties of three components of the SMFL field as well as their utility for defect characterization are investigated.

2. Finite element modeling and numerical simulation

SMFL fields due to known defects in ferromagnetic specimens can be modeled by solving Maxwell’s equations using the FEA method [2]. The ANSYS software uses Maxwell's equations as the basis for electromagnetic field analysis. The primary unknowns (degrees of freedom) that the finite element solution calculates are magnetic and electric potentials. Other magnetic field quantities such as magnetic field flux density, current density, energy, forces, loss, inductance and capacitance are derived from these degrees of freedom. Depending on the element type and element option, the degrees of freedom may be scalar magnetic potentials, vector magnetic potentials or edge flux, as well as non-time integrated and time integrated electric potential.

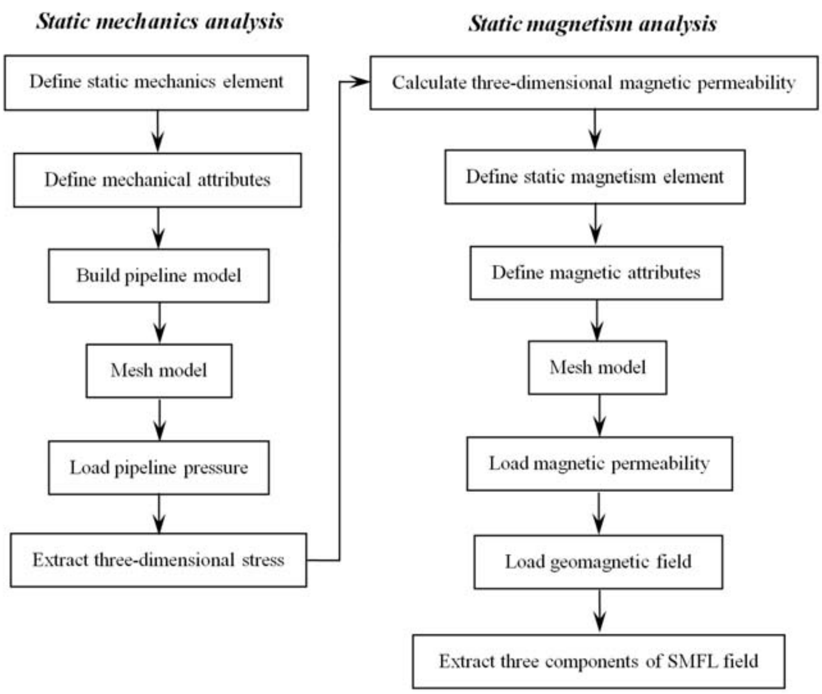


Fig. 2 Magneto-mechanical coupling scheme for pipeline magnetic testing

The procedure for doing a magneto-mechanical coupling analysis is shown in Fig. 2, which consists of ten main steps: (1) create the mechanics environment, (2) build the model and assign mechanical attributes to each region within the model, (3) mesh the model, (4) apply boundary conditions and load mechanics excitation, (5) obtain the solution and extract stress, (6) build magneto-mechanical coupling model, (7) create the magnetism environment, (8) assign magnetic attributes to each region within the model and mesh the model, (9) apply boundary conditions and load magnetic excitation, (10) obtain the solution and review the results.

In this paper, SOLID 45 and SOLID 96 are defined respectively as element type for static mechanics and static magnetism analysis. The nonlinear structural 3-D FEA model is shown in Fig. 3. The pipeline wall is specified to be grade X70 with diameter of 146mm, wall thickness of 10mm, and length of 1500mm. The pipeline defect is a outer surface hole and the radius is cycled between 2 and 6 mm. The hole penetrate 40% through the pipeline wall. The mechanical properties of X70 steel are shown in table 1. The amplitude of axial geomagnetic field is taken to be 40 A/m and fine mesh is generated within the problem region of interest in order to get better results. The magneto-mechanical coupling equation is given by [6]

$$\mu = \mu_{\mathrm{T}}(1 + bH / \mu_{\mathrm{T}})[a_0 + a_1 |\sigma|^m e^{n|\sigma|}] \quad (1)$$

where σ is the stress, T is the temperature, μ_{T} is the initial magnetic permeability relating to T, b is a constant relating to material properties, and a_0, a_1, m, n are the coefficients depending on the direction and value of applied stress. Eq. (1) shows that the relation between magnetic permeability and stress is nonlinear, including the power function and exponential function. Accordingly, the magnetic permeability increases rapidly and the ferromagnet is liable to be magnetized when the stress goes up. For X70 steel, b=2.5, μ_{T} =285, if σ<50MPa, a_0=0.76804, a_1=0.00916, m=1.90412, n=-0.03353, and if σ≥50MPa, a_0=-0.00447, a_1=0.04108, m=1.55499, n=-0.03148.

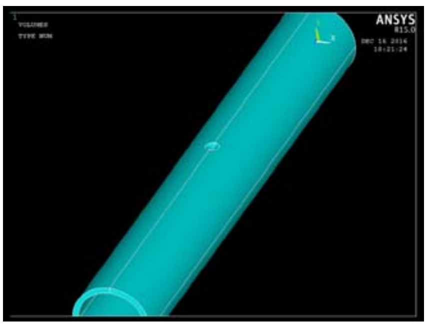
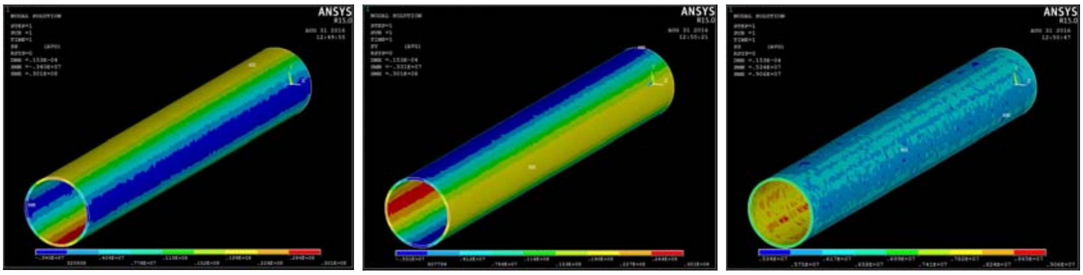


Fig.3 Three dimensional FEA structural model for pipeline

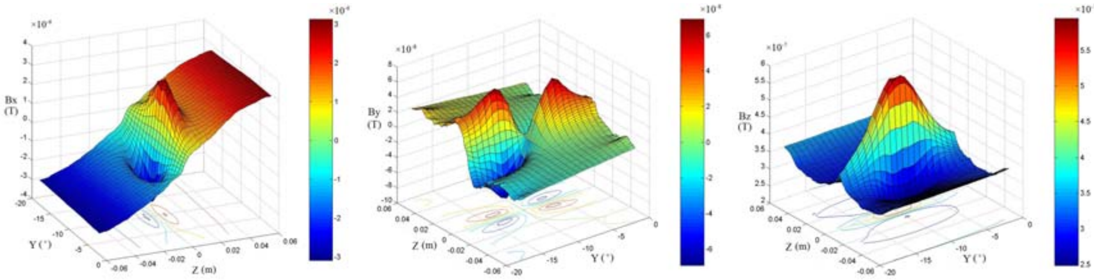
Table 1 Mechanical properties of pipeline

Material	Elastic modulus (GPa)	Poisson radio	Yield strength (MPa)	Density (kg/m^3)
X70	210	0.3	483	7850



Circumferential stress　　Radial stress　　Axial stress

Fig. 4 Color contour plots of the pipeline stress field

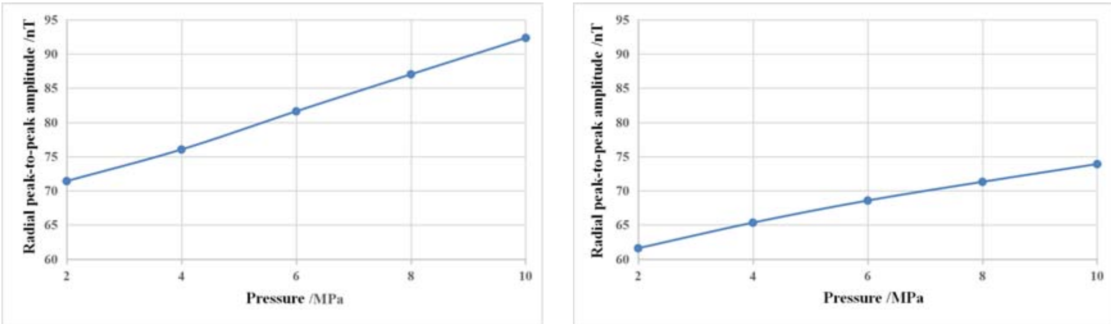


Radial component　　Circumferential component　　Axial component

Fig.5 Surface mesh plots of the SMFL field components

Fig. 4 shows the color contour plots of the radial, circumferential, and axial stress of the pipeline, respectively. Fig. 5 shows the surface mesh plots of the radial, circumferential, and axial components of the SMFL field, respectively. The axial component is the only field component that does not change polarity and is primarily indicative of the magnetic flux density induced in the pipeline wall. Though studies have shown the axial signal has some indication on defect depth and length, it can not be solely relied upon for high accuracy results. The radial component ideally has a unique bipolar nature and an effective zero bias level. Studies have shown that defect length can be extremely well defined by the location of the peaks, with the radial amplitude induced by the defect having a high correlation in estimating defect depth. Like the radial component, the circumferential component is bipolar in nature and has a zero bias. However, unlike the radial component it also is bipolar in the circumferential direction. The locations of the peaks are extremely well correlated with defect length and width. Another observation to note is the magnitude of the radial component is 10 to 15 times smaller than either that of the axial component, and the magnitude of the circumferential component is 100 times smaller than either that of the axial component.

Fig. 6 shows the effect of pipeline pressure on the defect peak-to-peak amplitude of radial SMFL component which clearly illustrates an increase in defect SMFL amplitude with increasing pipeline pressure.



defect with radius of 2mm　　defect with radius of 4mm

Fig. 6 An increase in the defect SMFL amplitude with increasing pipeline pressure

3. Conclusion

Compared with magnetic scalar testing, magnetic vector testing has more advantages and could provide more information about the defect. In this paper, based on numerical simulations carried out in ANSYS electromagnetic field analysis, a nonlinear structural tridimensional FEA model is created for pipeline magnetic testing and the magneto-mechanical coupling scheme is described. The spatial distribution and properties of three components of spontaneous magnetic flux leakage are also investigated. According to numerical simulations, an increase in the magnetic peak-to-peak amplitude of radial SMFL component is observed with an increase in the pipeline pressure. The relationship between pipeline parameter and magnetic signals could be utilized in the magnetic testing technique to characterize the pipeline defects.

Acknowledgements

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