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Analyses of magnetic field in spiral steel pipe

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ABSTRACT

In order to confirm the feasibility of identifying the girth welds using the magnetic field in spiral pipelines, the distributions of the magnetic field in spiral steel pipes with different sizes and different magnetizations were analyzed using the equivalent magnetic charge method, and were verified experimentally. The magnetic field inside spiral steel pipes is generally uniform with very small magnetic sudden changes at the spiral welds, whereas the magnetic field near the pipe ends has very big local changes. The size of spiral pipes, including its wall thickness, length, diameter, and the lift-off, has various influences on the local magnetic sudden changes at the spiral welds (LMASW) and the magnetic incremental near the pipe ends (MINPE), whereas the difference between LMASW and MINPE is always quite considerable. The bigger the radial magnetization component is, the bigger the difference between LMASW and MINPE is. When the radial magnetization component is small, changes of the circumferential and axial magnetization components can reduce this difference. Since the magnetizations of each pipe are seldom identical, the magnetic field inside each pipe is usually quite different. Thus there will be a big local magnetic sudden change at the girth weld inside the spiral pipeline, and this sudden change is much stronger than LMASW. Therefore, we can still consider identifying the girth welds using the magnetic field in spiral pipelines to improve the positioning accuracy of the in-pipe detector.

1. Introduction

Pipelines are the most important infrastructure used for transportation of oil and gas. Any early defect of pipelines, such as irregularities in a welded seam, corrosion, or a material defect, may grow into cracks or holes, which can expand to large leaks, and even lead to pipeline burst. The consequences are not only loss of product and expensive failures, but also very costly environmental pollution. So early defects and damages detection is of the greatest importance for pipelines.

Smart PIG (Pipelines Inspection Gauge) [1–4] and smart ball [5] are multi-parameter in-pipe detectors used most widely for such detection of pipelines' early defects and damages. Because there is a strict one-to-one correspondence between the pipeline defect measured by the in-pipe detector and the position of the pipeline or the detector, we have to calculate accurately the position of the detector in pipelines on every moment. The usual positioning methods used by the in-pipe detector, such as mileage wheel method [6] and strapdown inertial navigation system (SINS) method [7], require above ground marker (AGM) utilizing satellite signal as auxiliary positioning method to eliminate the cumulative error [8–10]. It is very inconvenient to install AGM along pipelines, and AGM is also very expensive [11]. Some models of AGM can increase the volume, weight and power dissipation of the in-pipe detector. Furthermore, it is more difficult to apply AGM to positioning the detector in subsea pipelines.

During the oil and gas pipeline detection experiments, our research group found that the magnetic field at the girth welds in pipelines is significantly different from that of other positions in pipelines. If we can identify the welds using the sudden changes of the magnetic field near the girth welds, we can easily judge when the in-pipe detector passes through a certain girth weld whose position along the pipelines can be got from the pipeline construction information, thus achieving the precise position of the detector. We can calculate mileage $s(t)$ at any moment t using (1), where l_i represents the length of each section of pipelines, got from construction information, and t_i represents the moment when the ith girth weld appears. Furthermore, this method is a passive detection with low power consumption, and the sensor used here does not require special coordination with the pipe wall. It therefore can avoid using the ground marking devices and will

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provide a new method that is more convenient and with low cost used for the precise location of the in-pipe detector.

$$s(t) = \sum_{i=1}^{k} l_i + \frac{t - t_i}{t_{i+1} - t_i} l_{k+1}, \quad t_i \le t < t_{i+1} \tag{1}$$

However, many of subsea pipelines are composed of a lot of welded spiral steel pipes. The spiral steel pipe is made from band steel. The band steel is extruded and helically convolved into a cylindrical raw tube at room temperature, and then the cylindrical raw tube is helically welded into a spiral steel pipe. Since it undergoes alternating squeeze before helically convolved and welded into a spiral pipe, the band steel is susceptible to a uniform magnetization in a single direction by the geomagnetic field, which forms a stable magnetic field around the band steel. But after the band steel is helically convolved and welded into a spiral pipe, the uniform magnetization in a single direction is equivalent to a spiral magnetization, which resulting in a redistribution of the magnetic field inside and outside the spiral pipe. The local magnetic sudden changes at the spiral welds (LMASW) and the magnetic incremental near the pipe ends (MINPE) should be special. Is LMASW too strong? Is MINPE which is responding to girth welds strong enough? Are they too similar to identify the girth welds using the magnetic field in pipelines? So it is essential to clarify the distribution characteristics of the magnetic field in pipelines.

The equivalent magnetic charge method can effectively determine the distribution of the magnetic charge density on the surface of the ferromagnetic material and then can easily calculate the magnetic field distribution around it [12]. A number of literatures had reported the characteristics of axial uniform magnetization to non-ellipsoid using the numerical method, achieving a lot of meaningful results [13–17]. However, the authors just analyzed the distribution characteristics of the magnetic charge density, but did not involve the distribution of the magnetic field inside the pipe.

The authors of [18] analyzed in detail the distribution characteristics of the magnetic field in a single seamless pipe using the equivalent magnetic charge method, and assumed the reason why there are sudden changes of the magnetic field near girth welds is that the magnetic field is approximately uniform inside the pipe far away from the ends, but has very big changes near to both ends of the pipe. The authors of [19] measured the magnetic field in pipelines with a smart ball, observed big magnetic sudden changes at the girth welds, and proposed the method to identify and position the girth welds utilizing the magnetic field in pipelines. Aforementioned previous researches are only for seamless steel pipe with a premise that the pipe is uniformly magnetized in a single direction, are therefore not entirely applicable to the analyses of the magnetic field inside a spiral steel pipe.

In this paper, the magnetization model of the spiral steel pipe will be analyzed in detail. The distribution characteristics in spiral steel pipes will be discussed comprehensively by means of both numerical calculation and experiments. A detailed comparison of the characteristics of LMASW and MINPE, the latter of which is responding to the girth welds, will be drawn in order to confirm the feasibility of identifying the girth welds in spiral pipelines utilizing the magnetic field inside the pipelines.

2. Numerical analyses

2.1. Method of analyzing

As shown in (2), magnetic flux density $\boldsymbol{B}_s$ in the spiral steel pipe consists of $\boldsymbol{B}_e$, $\boldsymbol{B}_m$, and $\boldsymbol{B}_p$, wherein, $\boldsymbol{B}_e$ denotes the geomagnetic field, $\boldsymbol{B}_m$ is the remanent magnetic field of the spiral pipelines assuming the pipelines is uniformly magnetized in a single direction by $\boldsymbol{B}_e$, and $\boldsymbol{B}_p$ comes from the redistribution of the remanent magnetic field of the band steel that is uniformly magnetized in a single direction by $\boldsymbol{B}_e$ before the band steel is helically convolved and welded into a spiral pipe. To calculate $\boldsymbol{B}_m$, the external magnetic charge density is calculated first of all by using (3) with the equivalent magnetic charge theory [20], and the spiral pipe is regarded as a whole. To calculate $\boldsymbol{B}_p$, the band steel is considered as a whole before it is helically convolved, the external magnetic charge density is calculated first of all by using (3) with the equivalent magnetic charge theory [20]. In (3), $\boldsymbol{r_s}$ is the position vector of a point on the surface of the magnet, $\boldsymbol{r}'$ is the position vector of any point on the surface excluding $\boldsymbol{r_s}$ of the magnet, $\boldsymbol{H_0}$ is the magnetic field used to magnetize the magnet, $\boldsymbol{n}$ represents the unit outer normal vector at a point $\boldsymbol{r}'$ on the surface of the ferromagnetic material, μ_r is the relative permeability of the magnet, and μ_0 is the permeability of vacuum.

$$\boldsymbol{B}_s = \boldsymbol{B}_e + \boldsymbol{B}_m + \boldsymbol{B}_p \tag{2}$$

$$\frac{1}{4\pi}\left(\int_{S'} grad \frac{\sigma(\mathbf{r}')}{|\mathbf{r}_s - \mathbf{r}'|} dS'\right)\cdot\mathbf{n} + \left(\frac{1}{2} + \frac{1}{\mu_r - 1}\right)\sigma(\mathbf{r}_s) = \mu_0 \mathbf{H}_0(\mathbf{r}_s)\cdot\mathbf{n} \tag{3}$$

The surface of the spiral steel pipe or the band steel is divided into N small surface element, for any surface element S_i, its position vector is marked as $\boldsymbol{r}_i$ and the distribution of its magnetic charge density σ_i is approximately constant, $\boldsymbol{H}_0 = \boldsymbol{B}_e/\mu_0$. When $\boldsymbol{r}_s$ is taken to the $\boldsymbol{r}_j$, (3) is discretized according to (4), and then we can get (5). We can use the numerical methods to calculate the distribution of the magnetic charge density σ_{mj} for $\boldsymbol{B}_m$ at any point on the surface of the spiral steel pipe and the distribution of magnetic charge density σ_{pj} for $\boldsymbol{B}_p$ at any point on the surface of the band steel. After the band steel is helically convolved and welded into a spiral pipe, the new position of σ_{pj} become identical to that of σ_{mj} on the spiral pipe.

$$\begin{aligned}\int_{S'} grad \frac{\sigma(\mathbf{r}')}{|\mathbf{r}_s - \mathbf{r}'|} dS' &= \sum_{\substack{i=1 \\ i\ne j}}^{N} \sigma_i \int_{S_i} grad \frac{1}{|\mathbf{r}_j - \mathbf{r}_i|} dS \\ &= \sum_{\substack{i=1 \\ i\ne j}}^{N} \sigma_i \int_{S_i} \frac{\mathbf{r}_j - \mathbf{r}_i}{|\mathbf{r}_j - \mathbf{r}_i|^3} dS\end{aligned} \tag{4}$$

$$\frac{1}{4\pi}\left(\sum_{\substack{i=1 \\ i\ne j}}^{N} \sigma_i \int_{S_i} \frac{\mathbf{r}_j - \mathbf{r}_i}{|\mathbf{r}_j - \mathbf{r}_i|^3} dS\right)\cdot\boldsymbol{n} + \left(\frac{1}{2} + \frac{1}{\mu_r - 1}\right)\sigma_j = \boldsymbol{B}_e\cdot\boldsymbol{n} \tag{5}$$

The magnetic field at any point in space is determined by the magnetic charge density on the surface of magnet. As shown in (6).

$$\boldsymbol{H}_d(\mathbf{r}) = -\frac{1}{4\pi}\int_S grad \frac{\sigma(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} dS' \tag{6}$$

For the discretized distribution of the magnetic charge density, according to (4) and (6), the magnetic intensity and the magnetic flux density at an arbitrary point inside or outside the spiral pipe can be expressed as (7)–(10), wherein $\boldsymbol{r}_j$ denotes the position vector of the jth surface element on the spiral pipe surface.