Research on AC FSM used in internal corrosion monitoring for oil & gas pipeline

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Abstract. This paper explored the possibility of using the AC FSM for internal corrosion inspection of pipelines without destruction. Principle analysis and numerical simulations were used to gain an insight into the AC current distribution in the material and to improve the probes configuration that installed on the outside surface of pipeline. The experimental setup for monitoring based on AC FSM was carried out, the main advantage of which is the currents injected are much smaller over existing commercial systems, the corresponding system security improved. At last, the applications showed that AC FSM system can successfully inspect the defects in the pipelines.

1. Introduction

Internal corrosion monitoring is commonly used in oil & gas pipelines for a wide range of applications, but most of the monitoring techniques, such as hanging slice method, electric resistance probe (ER) method and so on, have been utilized are intrusive which may bring new potential safety hazard. Comparing with the corrosion monitoring techniques, inspection methods are costly and low sensitivity, not able to monitor the growth of defects, have limited value for corrosion control [1].

The field signature method (FSM) is one of non-destructive methods for monitoring internal corrosion of pipelines [2]. At present, all the commercially available systems based on FSM that have been used for industrial application are all using DC input, in order to produce a measurable large signal which need to inject high value currents [3]. However, large currents will easy to produce spark and give rise to uncertainty in the measurement [4, 5].

In order to avoid above shortcomings, AC input is preferred over DC input from a practical point of view, the system based on AC FSM is developed for internal corrosion monitoring and proposed in this paper, which has achieved good results [6-8].

2. The theory of AC FSM

The theory of AC FSM is based on the measurement of increase in electric resistance, caused by presence of corrosion between measuring probes in the electrode matrix installed on the outside surface of the pipeline as shown in Figure 1 [9].

The parameter $FC$ is defined for analyzing corrosion rates and accumulated corrosion, which is calculated according to the expression as follows [10]. The voltage between two selected electrodes in the monitoring electrode matrix is compared with the voltage between reference electrodes and to the corresponding initial values when monitoring started [11]. The reference electrodes located in the area without corrosion in the vicinity of the monitoring electrode matrix.
Where \( V_0 \) is voltage at start-up, \( V_t \) is voltage at time \( t \), \( V_0' \) is voltage for reference pair at start-up, \( V_t' \) is the voltage for reference pair at time \( t \).

The electromagnetic field analysis is performed starting with the Maxwell equations, as follows:

\[
\nabla \times \overline{E} = \frac{\rho}{\varepsilon} \tag{1}
\]

\[
\nabla \times \overline{E} = -\frac{\partial \overline{B}}{\partial t} \tag{2}
\]

\[
\nabla \cdot \overline{B} = 0 \tag{3}
\]

\[
\nabla \times \overline{B} = \mu_0 \frac{\partial \overline{E}}{\partial t} + \mu_0 \overline{J} \tag{4}
\]

In the above equations, \( \overline{E} \) is the electric field density and \( \overline{B} \) is the magnetic flux density, \( \overline{J} \) is the current density. And \( \varepsilon, \rho, \mu \) are permittivity, charge density, magnetic permeability of the materials respectively. For \( \bar{J} = \sigma \overline{E} \) and \( \sigma \) the electric conductivity, Equations (1) and (4) are reduced to

\[
\nabla \cdot \overline{E} = 0 \tag{5}
\]

\[
\nabla \times \overline{B} = \mu_0 \frac{\partial \overline{E}}{\partial t} \tag{6}
\]

And the distribution of the electric field according to Helmholtz Equation which satisfies the following equation

\[
\nabla^2 \overline{E} = \frac{\sigma}{\mu} \frac{\partial \overline{E}}{\partial t} \tag{7}
\]

![Figure 1. The FSM schematic diagram.](image)

3. The simulation of AC FSM

The Figure 2 and Figure 3 illustrate the AC current path in the case of specimens with single notch and double notch at three different frequencies, that are 0.1Hz, 50Hz and 1 kHz. All the specimens are 300 mm long, 100 mm wide, 40 mm thick and the separation between the currents injecting electrodes are
set to 20 mm and the voltage drop electrodes are 10 mm. The notch is 10 mm deep, 1mm wide, double notches are separated by 10 mm.

**Figure 2.** The block with single notch: a) 0.1 Hz, b) 50 Hz, c) 1 kHz.

**Figure 3.** The block with double notch: a) 0.1 Hz, b) 50 Hz, c) 1 kHz.

It can be noticed that, the defect alter the path of the currents, the penetration depth is controlled by the frequencies, which will be forced squeeze to the surface flow as the frequency increasing through the skin effect. At very low frequency the current form an envelope around the defect, and follow closely the profile at higher frequencies. Then, AC FSM can achieve the same result against DC FSM through controlling the frequency of AC input with no need for high current injection.

4. The experimental setup for AC FSM

Figure 4 shows the block diagram of the setup, firstly, injecting the AC current through the injection electrodes welded onto the outside surface of pipeline, then flowing past the measuring module which was composed of array of equally-spaced probes. All combinations of adjacent electrodes in the array will be covered through repeating the measurements by the channel selection module. The measured signal is amplified to achieve the requirement of acquisition module, by fed signal through a preamplifier and then read with a lock-in amplifier. At last, the measured voltage is acquired by acquisition module and displayed.

**Figure 4.** The experimental setup for AC FSM.

5. Experimental validation

For the experimental test, two flat-bottomed plates with machined six square defects, $S_i$ ($i=1, 2, 3, 4, 5, 6$) shown in Figure 5(a) and six circular defects, $C_i$ ($i=1, 2, 3, 4, 5, 6$) shown in Figure 5(b) respectively.
Figure 5. The test plates with defects: a) square defects, b) circular defects.

The defects were manufactured with different depth, the dimensions of square defects and circular defects are listed separately in Table 1 and Table 2.

Table 1. Dimensions of square defects.

| Defect series | S1  | S2  | S3  | S4  | S5  | S6  |
|---------------|-----|-----|-----|-----|-----|-----|
| Length×Width (mm) | 30×16 | 30×16 | 30×16 | 16×30 | 16×30 | 16×30 |
| Depth (mm)   | 1   | 3   | 5   | 1   | 3   | 5   |

Table 2. Dimensions of circular defects.

| Crack series | C1  | C2  | C3  | C4  | C5  | C6  |
|--------------|-----|-----|-----|-----|-----|-----|
| Diameter (mm) | Φ30 | Φ30 | Φ30 | Φ20 | Φ20 | Φ20 |
| Depth (mm)   | 1   | 3   | 5   | 1   | 3   | 5   |

The setup described in section 4 is pictured in Figure 6. The low-frequency AC currents were injected in the plates. The defects with the same geometrical shape are measured together, so the measurements for each plate were carried out twice, operated as the left hand part and the right hand part separately.

Figure 6. Experimental platform.

For the plate with square defects, the measurement results of left hand part and the right hand part are displayed in Figure 7. And the measurement results of left hand part and the right hand part for the plate with circular defects are displayed in Figure 8. The bars in diagrams stand for the values of parameter $FC$, it can be found that the height of bars at the defect position is higher than the other areas.

Put all the data in one chart in Figure 9, let $S_L$ stand for square defects left hand part for short, the rest of the similar. It is found that for square defect with the same shape, the $FC$ values are proportional to the depth of the defect. And the $FC$ values in the positions around the defect are also affected, increasing as approaching to the defect.
When the length of defect is close to the space of pair of electrodes, the $FC$ values will significantly rise along with the defect depth increasing, reflecting the real condition of corrosion. Similarly, the length-width ratio is also the variate that influencing the $FC$ value.

For the circular defect, with the same defect depth, the $FC$ value will increase along with the diameter getting larger, obey the same laws with the square defect. All of the above illustrated that using AC FSM can monitoring the corrosion effectively.

Figure 7. The results of the plate with square defect: a) left hand part, b) the right hand part.
Figure 8. The results of the plate with circular defect: a) left hand part, b) the right hand part.

Figure 9. Curves of $FC$ values.
6. Conclusions
In summary, the theoretical formulae based on AC FSM have been deduced and the Comsol Multiphysics was used to analyse AC distribution with three different frequencies in intact specimens. A novel experimental setup was developed with low-frequency AC input against commercially available DC FSM system and the injected currents of novel system are much smaller. The tests show that the AC FSM system can reconstruct the position and also reflect the size of the defects effectively.

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