Simulation on the Effect of Frequency and Ferromagnetic Tubes Specifications by Far Field Eddy Current Examination

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Abstract. Tube leakage frequently occurred in on-service fossil power plants. Traditional NDT testing methods, including RT, UT, MT and PT are not applicable for the examination of large amount tubes. Fat eddy current examination is a new technique for testing ferromagnetic tubes defects, such as inner corrosion, thickness reduction and cracks. Far field eddy current simulation and verification for different specification tubes has been carried out. The result shows that the position of far field eddy current moves backwards with the increase of wall thickness and tube ID. To the defects with same size, examination sensitivity is higher in far field eddy current area. When the defect with same size locates in the inner and outer surface of the tube, the change of magnetic intensify differences is approximately the same, which is in accordance with the experimental result and is satisfied with far field eddy current examination theory. It has been concluded that defects in ferromagnetic tubes could be judged and recognized by far field eddy current examination technique, which shows prospective for the on-line examination and safety evaluation for in-service tubes in fossil power plants.

Keywords: Far field eddy current; Simulation; Heat exchanger tube; Detection mechanism.

1. Introduction

Tube leakage frequently occurred in on-service fossil power plants, which causes economic loss and even threats the safety of the nearby workers. The quick on-line testing method are highly focused[1]. Traditional non-destructive testing methods, including RT, UT, MT and PT are not applicable on the large amount of on service tubes in the fossil power plant. Far field eddy current examination is a new technique to test the inner defects of the tubes and to avoid future leaking[2-3]. Far field eddy current technique is an examination method acquired from traditional eddy current testing. The inner corrosion, depth reduction and cracks are directly tested by the preset coil[4-8]. For instance, tubes in different part of the boiler have different specifications, this paper proposed far field eddy current testing simulation for different specification tubes with different defects[9-12]. Simulation has been carried out to verify and quantitative far-field eddy current theory.(1)Defects with same size at different position tested under different eddy current frequencies have been simulated to determine the best frequency scope. Mutual verification on 2-3 times of tube diameters, which has been reported the best far field position published papers references have also been carried out to determine the best receiving position. Theoretic support has been provided for the probe design and manufacturing in further research.(2)The inner surface examination sensitivity is higher than the outer surface compared with traditional inner through examination method. Simulation
has been carried out to verify if the examination sensitivity at the inner and outer surface is in accordance.(3) In traditional far field eddy current theory, no conclusion has been drawn on the influence of inner diameter and wall thickness on far field area position besides the 2-3 times diameters result for the best sensitivity. This paper will verify the influence of wall thickness and tube diameter on the far field area position\textsuperscript{[13-15]}.

2. Establishment of Axial Symmetry Simulation Model

When low frequency AC goes through the exciting coil, a low frequency time-changing magnetic field $B$ will be induced around the coil. According to Faraday’s law of electromagnetic induction, a time changed eddy current will excite a time-changing vortex electric field $E$. An eddy current field $J_e$ will be formed in the inner wall of a metal based tube. So the magnetic field in the space around the exciting coil is the sum of vectors of the magnetic fields from the electric field $J$ caused by the conducting current in the coil and the eddy current field $J_e$. The displacement current caused by the time-changing vortex electric field should be omitted due to low frequency. The electromagnetic field in the space around the exciting coil fits the following Maxwell equation,

\begin{equation}
\nabla \times H = J + J_e \\
\n\nabla \times E = -\frac{\partial B}{\partial t} \\
\n\nabla \cdot B = 0 \\
\n\nabla \cdot D = 0
\end{equation}

With vertex magnetic displacement, there is:

\begin{equation}
B = \nabla \times A
\end{equation}

Put formula (2) into (1) and without considering the constant field, there is:

\begin{equation}
E = -\frac{\partial A}{\partial t}
\end{equation}

\begin{equation}
J_e = \sigma E = -\sigma \frac{\partial A}{\partial t}
\end{equation}

Put (4) into the first equation of (1), there is:

\begin{equation}
\nabla \times \left( \frac{1}{\mu} \nabla \times A \right) = J - \sigma \frac{\partial A}{\partial t}
\end{equation}

(5) is the diffusion equation which describing the far field eddy current phenomena of the exciting coil near the inner and outer surface of the metal tube. To the time-harmonic electromagnetic field, (5) could be simplified as:

\begin{equation}
\frac{1}{\mu} \nabla^2 A = -J + j \omega \sigma
\end{equation}

J-density vector of conduction current, A-complex amplitude vector of vector magnetic potential. In the cylindrical coordinate, both $J$ and $A$ only have components in $\theta$ direction and $A$ is just the function of $r$ and $z$. So under the condition of axial symmetry,(7) is simplified as:

\begin{equation}
\frac{1}{\mu} \left( \frac{\partial^2 A}{\partial r^2} + \frac{1}{r} \frac{\partial A}{\partial r} + \frac{\partial^2 A}{\partial z^2} - \frac{A}{r} \right) = -J + j \omega \sigma A
\end{equation}

Solving equation(7)with FEM, the space distribution of far field eddy current could be got\textsuperscript{[17-18]}. The widely adopted ferromagnetic heat exchanging tubes are used in the model. Tube material is carbon steel with OD 16mm and thickness 4mm. The winding has 500 turns copper conductor with
0.1A and 50Hz AC current. Since the overall model is symmetric, 2D axial symmetric model has been adopted to replace 3D model for time saving. The meshing type is reflection and size is 0.1mm. The total grid cell number is 293815. The model consists of exciting coil, ferromagnetic tube and air. The inner diameter of the tube is 12mm and the wall thickness is 2mm. An artificial groove defect with 1mm width and depth is carved on the surface of the tube. The distance between the defect center and the exciting coil center is 20~100mm (step10mm).

3. Simulation for Defects with the Same Size under Different Frequency

3.1. Simulation for Defects under 50Hz
The distance from the defect to the exciting coil varies from 20 to 100mm. The step is 10mm. Figure 1 shows the simulation result of the signal change with defect position. The distance between the defect and the exciting is 50mm, the defect signal increases sharply then goes smooth. This means that the far field eddy current area under 50Hz is greater than 50mm. The peak position is 80mm, which corresponds the highest examination sensitivity.

![Figure 1. Difference of magnetic induction density with different locations under 50Hz](image1)

3.2. Simulation for Defects under 110Hz
Figure 2 shows the simulation result of the signal change with defect location. The distance between the defect and the exciting coil is 20mm, the defect signal increases sharply then goes smooth. This means that the far field eddy current area under 110Hz is about 20mm. The peak position is 20mm, which corresponds the highest examination sensitivity.

![Figure 2. Difference of magnetic induction density with locations under 110Hz](image2)

3.3. Simulation for Defects under 150Hz
Figure 3 shows the simulation result of the signal change with defect position. The distance between the defect and the exciting is 20mm, the defect signal increases sharply then goes smooth. This means that the far field eddy current area under 150Hz is about 20mm. The peak position is 20mm, which corresponds the highest examination sensitivity. And the sensitivity is lower than when the frequency is under 150Hz.
Figure 3. Difference of magnetic induction density with different locations under 150Hz

Figure 4. Difference of magnetic induction density due to defects locations under different frequencies

Figure 4 shows the combination of the maximum examination signal changes under 50Hz, 110Hz and 150Hz. For the ferromagnetic tube with 12mm OD and 2mm wall thickness, the examination sensitivity under 150Hz is the highest under the above 3 frequencies.

4. Simulation for the Influence On Examination Sensitivity to Defects at Inner and Outer Surface

In this part, magnetic induction density difference changes of the defects at the inner and outer surface of the tube with the same size has been simulated. The examination sensitivity at the inner surface and outer surface has been compared.

Figure 5 shows the simulation result. The blue line is the magnetic induction density difference caused by the inner surface defect, which is $2.927 \times 10^{-9} T$. The red line is the magnetic induction density difference caused by the outer surface defect, which is $4.043 \times 10^{-9} T$. The red line is mostly in coincidence with the blue line. This means that the examination sensitivity is almost the same when the defect is on the inner surface or the outer surface.

5. Simulation under the Same Diameter and Different Wall Thickness

Figure 5. Difference of magnetic induction density caused by defects outer and inner surface defect

Figure 6. Changes of log(Bz) with distance in different wall thickness of tube

A far field eddy current simulation model has been established, with the ID 12mm and the wall thickness 1, 3mm, 5, 7mm. Figure 6 shows the relationship of log(Bz) with distance under different tube wall thicknesses. The far field area size is short under 1mm wall thickness compared with 3mm wall thickness, which means the far field area will be reduced with the decrease of wall thickness. The curves under 5 and 7mm wall thickness coincidences and without transition point. This means that the
far field area does not exist when the wall thickness is greater than 5mm, because the magnetic force line could not get through the wall to form far field area.

6. Simulation under Different Inner Diameters and the Same Wall Thickness
This part is to verify if the distance shows 2-3 times of the inner diameter. The simulation model tube wall thickness is 2mm, and tube ID is 5, 10, 15 and 20mm. The relationship between log(Bz) and distance after simulation is shown in figure 7. It has been seen that the distance between far fields area increases with the increase of tube ID. The distance between far field area and exciting coil is 4-5 times of ID, which is greater than the theory 2-3 times of ID.

![Figure 7. Changes of log (Bz) with distance in different inner diameter of tubes locations of defects under 110Hz exciting frequency.](image)

7. Conclusion
This paper constructs a 2D axial symmetry model and determines the far field area position according to amplification and phase sudden change. It has been found that the sensitivity is higher in far field area compared with in near field area. The artificial defect is a groove with 1mm high and 1mm depth. The distance between the defect and the exciting coil is 20-100mm. Simulation shows that the magnetic induction difference change is approximately the same caused by the same size artificial defects in the inner and outer surface. Effects of tube wall thickness, diameter and frequency on far field eddy current area have been simulated. Far field area moves backward with the increase of wall thickness. When the thickness reaches certain value, no far field area will be formed due to the magnetic line could not goes through the wall. Far field area moves backward with the increase of tube diameter. Far field area moves forward with the increase of examination frequencies when from 50 to 150Hz. When the distance between the exciting coil and the tube center is greater than 57.5mm, the air indirect coupling energy is no longer zero. The far field area is determined from the energy coupling side.

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