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PROSTHETIC HEART VALVES EVALUATION USING ECT METHOD

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Abstract: *This paper deals with conductive prosthetic struts –heart valves evaluation using eddy current testing (ECT) method. Basic principles of ECT method, informations about heart valves and simulated problem description are described in the first part of this paper. Obtained simulation results, their interpretation and practical utilization are described in second part of the paper.*

Key words: *heart valves, eddy currents, magnetic vector potential, finite element method, coil impedance, material defect*

INTRODUCTION

Prosthetic heart valves are usually implanted when valve disease leading to stenosis or incompetence is indicated. One type of mechanical valve called the Bjork-Shiley Convexo-Concave (BSCC) heart valve was widely implanted between 1979 and 1986. These valves have a carbon occluder disc held in place by two metallic struts of which, the outlet strut is welded to the suture ring, while the inlet strut is integral to the valve suture ring.
Occasionally the weld at one end of the outlet strut fails. Although the patient does not experience any discomfort at this point, this may be a precursor to fracture at the other leg of the strut causing loss of the disc, which leads to fatality. As a result, there is considerable interest in detecting single leg separation (SLS) of the outlet strut in the heart valve [1] .
Nondestructive Evaluation (NDE) and Nondestructive Testing (NDT) create together an interdisciplinary field of study which are concerned with the development of analysis techniques and measurement technologies for the quantitative characterization of materials, tissues and structures by noninvasive means. Ultrasonic, radiographic, thermographic, electromagnetic, and optic methods are employed to probe interior microstructure and characterize subsurface features. Applications are in non-invasive medical diagnosis and on-line manufacturing process control, as well as the traditional NDE areas of flaw detection and materials characterization.

Eddy current testing (ECT) is essentially a near-surface technique. It is useful for detecting surface-breaking or near-surface cracking and variations in material composition. It can also be used for measuring the thickness of non-electrically conductive coatings on electrically conductive substrates. In most steels, eddy current testing is limited to surface examination due to the relatively high permeability of these materials. The inspection of welds in ferritic steels can be problematic as the response is dominated by changes in the magnetic permeability across the weld. However, special types of probes have been developed (differential coils) to lessen the effects to material changes and permit the detection of small flaws.

1 EDDY CURRENT TESTING

Eddy current inspection is one of NDT methods that use the fundamentals of "electromagnetism" as the basis for conducting materials examinations. Several other methods such as Remote Field Testing (RFT), Flux Leakage and Barkhausen Noise also use this principle [2].
Eddy currents are closed loops of induced current circulating in planes perpendicular to the magnetic flux- see Fig.1. They normally travel parallel to the coil's winding and flow is limited to the area of the inducing magnetic field. Eddy currents concentrate near the surface adjacent to an excitation coil and their strength decreases with distance from the coil as shown in the

Fig.1. Eddy current density decreases exponentially with depth. This phenomenon is known as the skin effect.

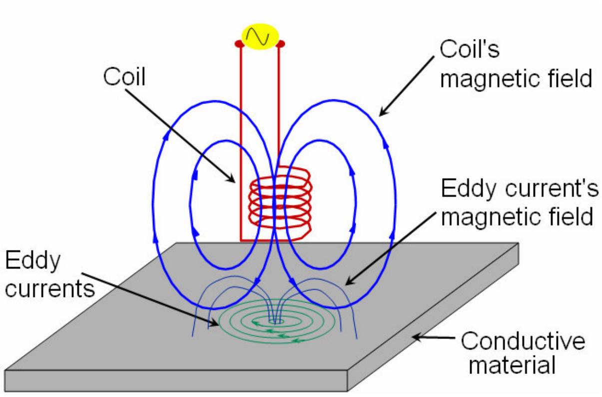

Fig. 1 - Electromagnetic interactions in ECT [2]

1.1 Electromagnetic field equations

Non – destructive evaluation using ECT method represents an electromagnetic wave propagation in conductive environment . This is characterized as general case , i.e. a non-stationary electromagnetic (EM) field . However for solution of this problem is used quasi-stationary EM field case.

This is the case when relatively slow time changes are presented, i.e. $\frac{\partial \vec{D}}{\partial t}$ is negligible to $\vec{J}$, in the 1. Maxwell`s equation, which corresponds to non-stationary EM field in conductive material. The Maxwell`s equations (1) are valid in form:

$$\mathrm{rot}\vec{H} = \vec{J} \quad \mathrm{rot}\vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{1}$$

$$\mathrm{div}\vec{B} = 0 \qquad \mathrm{div}\vec{D} = \rho_0$$

with additional material relations (2)

$$\vec{B} = \mu\vec{H} \qquad \vec{D} = \varepsilon\vec{E} \qquad \vec{J} = \gamma\vec{E} \tag{2}$$

The magnetic vector potential is given by the next relations (3):

$$\mathrm{rot}\vec{A} = \vec{B} \quad \text{and} \quad \mathrm{div}\vec{A} = 0 \tag{3}$$

Then if a homogenous, isotropic space is considered, potential solutions for the magnetic vector potential are given as follows (4):

$$\nabla^2\vec{A} = 0 \qquad \nabla^2\vec{A} = -\mu\vec{J} \tag{4}$$

$$\nabla^2\vec{A} - j\omega\omega\mu\vec{A} - \mu\sigma\nabla V = 0$$

$$\nabla.\sigma\left(-\nabla V - j\omega\vec{A}\right) = 0$$

These equations are required for quasi-stationary EM field case solution and to calculate vector potencial $\vec{A}$.

2 TYPES OF PROSTHETIC HEARTH VALVES

The human heart consists of the bicuspid and tricuspid valves. Bicuspid valves have two leaflets. One example of this type of valve is the mitral valve. Tricuspid valves have three leaflets. An example is the aortic valve. In general heart valves is to regulate the blood flow through the heart based upon pressure. The valve opens when the pressure on one side is greater than the other. It is estimated that a typical human heart valve opens and closes around 40 million times per year. This implies that heart valves are subjected to tremendous amounts of cyclic stress, which sometimes when combined to specific health factors lead to premature failure. The aortic and mitral valves are the most commonly replaced valves.

Prosthetic heart valves can be subdivided into three groups. One of these groups is the mechanical heart valve that allows unidirectional blood flow through mechanical closure of a ball and cage model or a pivoting or tilting disc valve. These valves can be constructed using various material combinations such as metal and polymers or plastics.

The other group is bioprosthetic valves, flexible trileaflet valve. These are harvested from pigs, fabricated from cow pericardial tissue and homografts or allografts obtained from cryo-preserved cadavers.

The third type of prosthetic heart valve is relatively new. These valves are polymer based flexible trileaflet valves. This type of valve is fabricated from biochemically inert synthetic polymers.

The heart valves may fail due to: degenerative valve calcification, (which is a direct consequence of aging), rheumatic fever, endocarditis and congenital birth defects. Manifestation of these diseases results in valvular stenosis, which is the obstruction of blood flow across the heart valve and mitral valve prolapse, also known as insufficiency or defective closing of the valve. When the symptoms become intolerable for a normal lifestyle, the normal course of action is to replace the damaged valve with an artificial one [3] .

3 BJÖRK-SHILEY CONVEXOCONCAVE HEART VALVE

The valve was developed to provide effective relief, with minimal complications, for patients with diseased native valves.

Figure 2 shows the BSCC valve with its tilting disc held in place by a large, fixed, inner strut and a smaller, welded, outlet strut. Fractures of the BSCC prosthetic heart valve's outlet struts and escape of the disc, resulting in embolization, massive regurgitation, and often death, began to be reported shortly after the valve's introduction [4].

Figure 2 – Photograph of BSCC prosthetic heart valve. Tilting disc is held in place between fixed inlet strut (foreground) and welded smaller outlet strut (background). Whiter outer material is sewing ring, [4]

Welded smaller outlet strut was the subject of our simulations. This strut is very often damaged . It is caused by the tilting disc motion. This strut has a thin wire shape and because of this , it can be idealized to cylinder shape with appropriate dimesions – see Fig. 4.

4 SIMULATION PROGRAM

Simulation program used for this problem was based on the Finite Element Method (FEM) and written in program language FORTRAN. Magnetic vector potential was computed in every grid node and graphic dependence of coil impedance change on probe direction was final representation of computer simulation.

5 SIMULATED PROBLEM DESCRIPTION

5.1 Coil description

The Pancake coil type was selected for simulation. This coil type is structural simply and regarding to it has no directional properties. Pancake coil type is also suitable for various defect bearings and it has the most sensitivity. A coil dimesions were selected in regard to the material defect dimensions – see Fig. 4. For this coil type was driving signal frequency f = 500 kHz. Because simulated problem dimensions were order of magnitude about decimals of milimeters and the higher resolving power is required the higher have to be signal frequency, 500 kHz value was selected due to this fact. On the order hand the higher will be a driving signal frequency the lower will be the equivalent penetration depth of a wave into the material , but in our case such frequency is suitable due to material and crack dimesions.

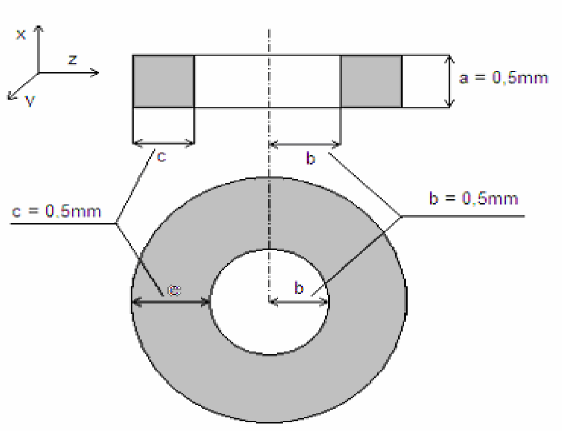

Figure 3 – Coil parameters description

5.2 Material description

The outlet strut , which was a subject of these simulations was replaced by conductive material. Material dimensions were adapted to the outlet strut dimesions. In this way was obtained a simplified model , which was more suitable in regard to avaibable software resources. Material dimesions are evident from Fig. 4. Electric and magnetic properties of the material were chosen to correspond with real values of material used for prosthetic heart valves .

$$\mu_r=1 \text{ [H/m]}, \quad \sigma= 1{,}4 .10^6 \text{ [S/m]}$$

Simulated material parameters are equivalent to material parameters used for prosthetic heart valves in biomedical praxis as follows:

Corrosion proof steel AISI type 301
Cobalt alloy 12 PM
Titan alloy Ti- 6Al- 4V (Titanium-Aluminium–Vanadium)

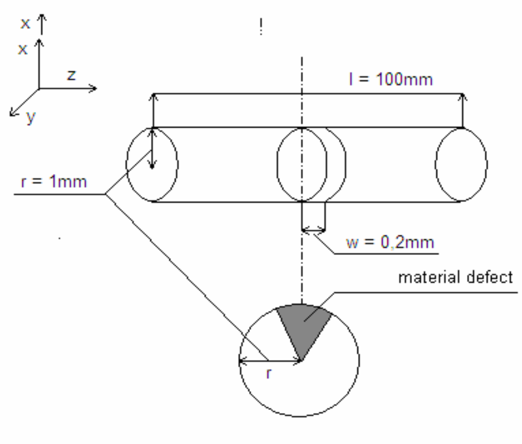

Figure 4 – Material dimensions description , [5]

5.3 Spatial structure of probe and material

Spatial structure of the material and probe throughout scanning is represented by Fig. 5. Distance between upper border of the material and lower border of the

probe was s= 1 mm. Probe motion along z axe was from <-10;10> with 1 mm scanning step. The whole defect was located in the middle of the material , where z =0 – see Fig. 5.
Width of the defect is w= 0,2mm. The depth of the defect was changed according to the depth values during simulations –see Fig. 5 .

Following the depth of the defect was also changed the defect opening angle φ see - Fig. 5. Five simulations with various depth of the defect at each one defect opening angle were performed according to Fig. 5. That means that 25 simulations were performed together.

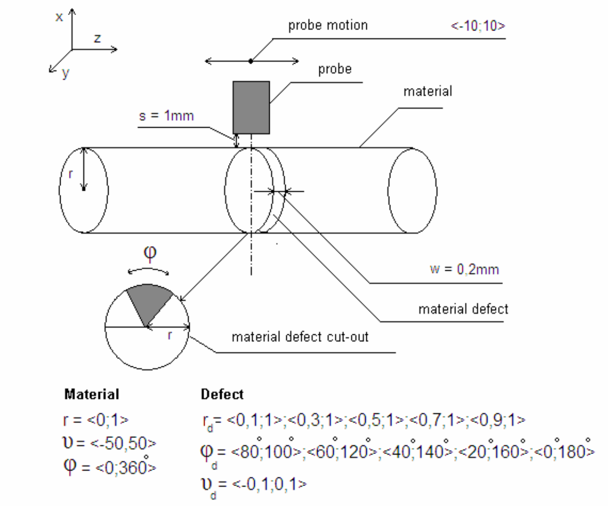

Figure 5- Coil and material spatial configuration , [5]

6 NUMERICAL SIMULATIONS RESULTS

Material and defect dimesions with the probe type (PANCAKE) and its properties were defined at the program language. The grid which spatial configuration was adapted to dimensions and localization of the defect was designed for the selected material.

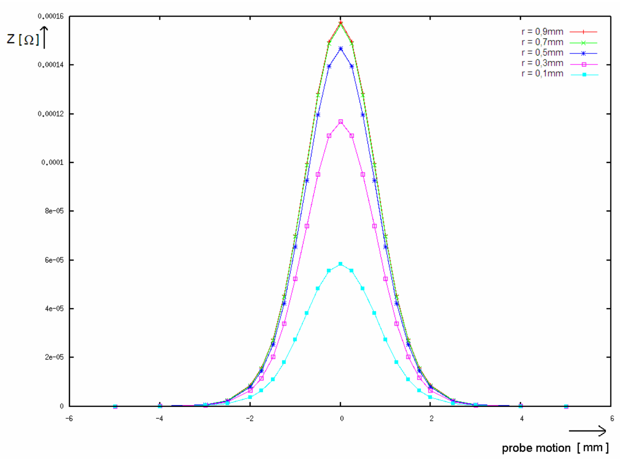

Figure 6 –Graphic dependence of coil impedance change on probe motion. Opening angle φ = <0°;180°>

Five waveforms displayed at Fig. 6 represent five depth of the defect values simulations for one opening angle value φ = <0°;180°> according to Fig. 5. The graph with the smallest amplitude (cyan color) represents the shallowest defect case r = 0,1 mm – Fig. 6. Gradually bigger amplitudes represent more deeper located material defect . Graphs for r_1=0,7 mm (green color) and r_2= 0,9 mm (red color , i.e. the biggest material defect value) are the same- see Fig. 6. This fact is caused by the quick saturation of conductive material, which has origin in driving coil frequency f= 500 kHz.

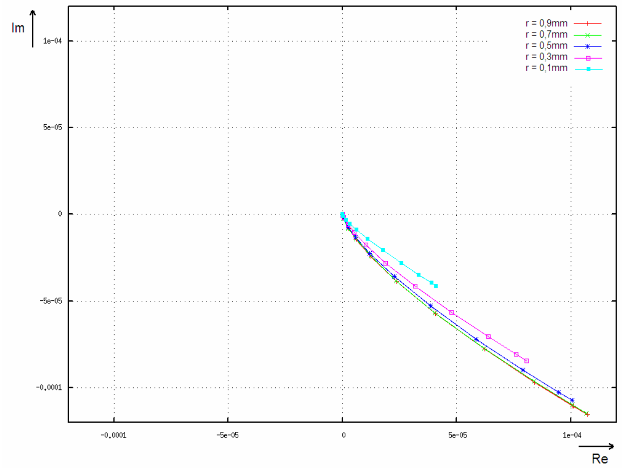

Figure 7 – Graphic dependence of imaginary on real part of impedance of the coil $|Z|$ for opening angle φ = <0°;180°>

As can be seen from Fig. 7 displayed at Gaussian plain , complex impedance module is finding at fourth quadrant and material defect opening angle can be evaluateed directly by this graphic form.

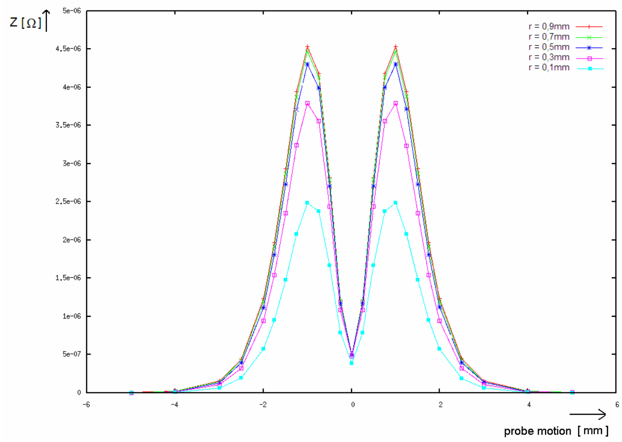

Figure 8 - Graphic dependence of coil impedance change on probe motion. Opening angle φ = <80°;100°>

Waveforms at Fig. 8 represent 5 simulations for various depths of the defect for one defect opening angle value φ = <80°;100°>. It can be seen that represention does not correspond with real material defect description, where the defect has approximately a triangle shape . The curve with two maximal values -- peaks (for one depth of the defect value) can be seen on Fig. 8. This is caused by small material defect opening angle . Path for eddy currents (which have to be enclosed and because they find a path with smaller resistance value) is shorter when they underflow the material defect in this case. This is shorter path unlike flow around the material defect.

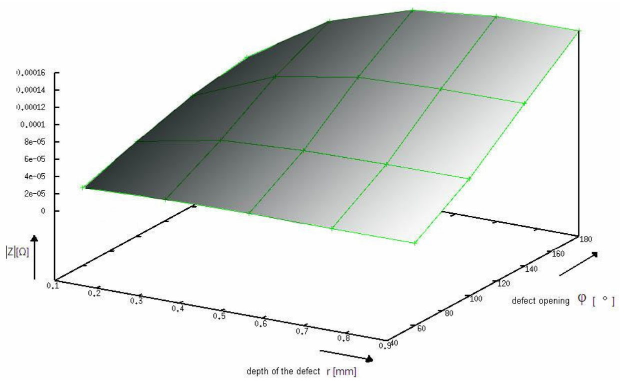

*Figure 9 – Three dimensional dependence of the defect opening angle **φ** on depth of the defect **r** and impedance change* $|Z|$

This 3D graph contains all 25 simulated problems as described above. Final results interpretation of this graph is following: Coil impedance change rise up markedly with the opening angle **φ** raising and with the depth of the defect raising **r**. It can be seen that the coil impedance change for r=0,1 mm and r=0,3 mm is lower in comparing with other r values. This fact is corresponding with smaller resistance path for the eddy currents. Finally can be said the larger will be the defect opening angle the larger will be the coil impedance change. The depth of the defect increasing has not so significant influence on coil impedance changes.

7 Conclusion

This paper deals with prosthetic heart valve evaluation using ECT method. An aim of performed numerical simulations was to show a suitability of ECT method for these kind of conductive materials inspection as prosthetic struts are. It can be said that materials and their defects with dimensions order of magnitude about decimals of milimeters can be inspected using ECT method in detail and with high resolution. However some complications about material defect location may occur when dimensions of a crack are too small. Then smaller resistivity path for eddy currents is different from real shape of a crack .Resulting information of an inspection does not correspond with real shape and localization of the defect in such case. This fact can be seen in our simulated problem when depth of the defect was r= 0,1 mm and r= 0,3 mm.

Prosthetic heart valves made from conductive materials are daily used in biomedical praxis. Using methods for nondestructive evaluation of conductive materials such as ECT provides very detailed inspection of these materials and this is the reason why this method can be applied to biomedical applications.

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