INSPECTION OF CONDUCTIVE PROSTHETIC REPLACEMENTS USING ELECTROMAGNETIC METHODS OF NON-DESTRUCTIVE TESTING

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Summary: This paper describes the use of electromagnetic methods of non-destructive testing for detecting of inhomogeneities presence in a prosthetic replacement with focus on strut fractures in prosthetic heart valves. In the first part of this paper there are described a basic principle of eddy current testing, heart valve replacement and materials which are usually used for it. The experimental part contains description of simulated problem, obtained simulation results and their interpretation for use in medicine.

1. INTRODUCTION

Prosthetic devices are being implanted at record levels as the nation "ages" and advances in prosthetic science are made. Devices that are implanted range from artificial limbs and hips to devices such as heart valves. Periodic evaluation of the state of the devices is of significant interest particularly in the case of prosthetics whose failure can be fatal. An example of such a device is the artificial heart valve. Heart valves are usually replaced when stenosis or incompetence are indicated. This article presents one new technique that has been developed for the detection of outlet strut failures in Bjork-Shiley heart valves. The prospective method includes a noninvasive electromagnetic technique used also in non-destructive testing of materials.

Nondestructive testing (NDT) and Nondestructive evaluation (NDE) create together an interdisciplinary field that plays an important role in science and in various application areas of industry and medicine. NDT methods are techniques for inspection of material objects without their damaging. Methods of NDE are techniques used not only for identification of defects in objects, but also for characterization of defects, i.e. measurement its size, shape, and orientation, determination of material properties and other physical characteristics. The most of NDT methods are used in medicine for diagnosis and online process controlling of operations.

One of the often used electromagnetic methods is eddy current testing (ECT), which is a method for detecting surface and near surface defects. The main advantage of eddy current inspection is its sensitivity to small defects which are also presented in a heart valve replacement.

2. EDDY CURRENT TESTING

Eddy current inspection is one of several methods that use the principal of electromagnetic field as the basis for materials inspection. The coil excited with alternating current of fixed frequency creates a primary magnetic field in its vicinity. If the coil is placed nearby the conductive material, the primary magnetic field in the coil induces electrical 'eddy currents' (EC) in the material, Fig.1, which concentrate near the surface adjacent to an excitation coil and their intensity decrease exponentially with depth. These EC generate secondary magnetic field of the opposite direction. The presence of a discontinuity on the surface of the inspected component will perturb the induced magnetic field and it will also affect the eddy currents. The eddy current variation is recorded by measuring the changes of electrical impedance of the coil. ECT can be used for detection of inhomogeneities, measurement of metal thickness, detection of metal thinning due to corrosion and erosion, fatigue cracks and the measurement of conductivity and permeability.

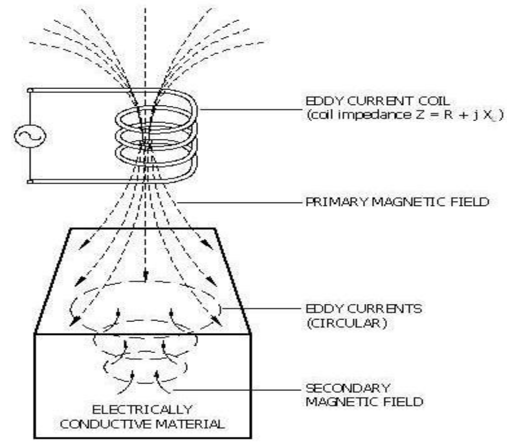

Fig.1: Principle of electromagnetic interaction in ECT

2.1 Electromagnetic field equations

ECT is based on the principle of electromagnetic induction. The explanation follows from electromagnetic field equations for conductive material which are described for quasistationary case of electromagnetic field. The condition of quasistationary case is $\mathbf{J} \gg \partial \mathbf{D} / \partial t$. Consequently the Maxwell' equations have following form

$$\mathrm{rot}\mathbf{H} = \mathbf{J}, \quad (1) \qquad rot\mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad (3)$$

$$\mathrm{div}\mathbf{B} = 0, \quad (2) \qquad \mathrm{div}\mathbf{D} = \rho, \quad (4)$$

and the material equations

$$\mathbf{B}=\mu\mathbf{H}, \qquad \mathbf{D}=\varepsilon\mathbf{E}, \qquad \mathbf{J}=\sigma\mathbf{E} \qquad (5)$$

The magnetic vector potential is defined for quasistationary case by following equations

$$\mathrm{rot}\mathbf{A} = \mathbf{B}\,, \qquad (6) \qquad \mathrm{div}\mathbf{A} = 0\,, \qquad (7)$$

The eddy current problem can be described mathematically by the next wave equation with harmonic excitation in terms of the magnetic vector potential

$$\nabla^2\mathbf{A} + k^2\mathbf{A} = -\mu\mathbf{J}\,, \qquad (8)$$

where **A** represents the magnetic vector potential that was counting in every node of our mesh using for numerical simulation, μ is the permeability of the media involved, **J** is the excitation current density, k^2=-j$\omega\mu(\sigma$+j$\omega\varepsilon)$ is propagation constant. This propagation constant is determined by material properties and frequency.

2.2 Impedance analysis of ECT

ECT method principle is based on impedance measurement of coil excited by alternating current. The impedance placed in a sufficient distance above the material can be described by network variable called complex impedance determined by relation

$$\dot{Z}_0 = R_0 + j\omega L_0\,, \qquad (9)$$

where R_0 represents resistance, i.e. losses in coil winding and L_0 represents self induction of a coil characterized by relation

$$L = \sum \phi / I\,, \qquad (10)$$

where ϕ represents flux of magnetic induction and I represents electric current passing through the coil.

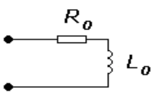

Fig. 2: Equivalent circuit of the coil in air

Considering that the coil is positioned in the vicinity of conductive material, the most flux of magnetic induction created by coil penetrates material and one its part is dissipated into air. Given system can be replaced by the scheme.

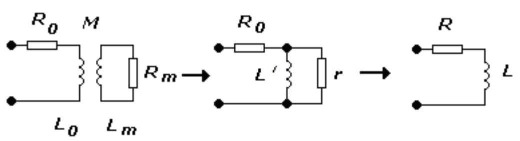

Fig.3: Equivalent circuit of probe on top of object without defect

where M represents the mutual inductance of the coil and material. The inductance L_m represents the material self induction and resistance R_m represents the thermal losses in material, [5].

In the case of material inhomogeneity the material properties change is represented by the change of the mutual inductance. This change appears in the resulting impedance as the increase of resistance and inductance.

The ideal coupling is considered for simple representation of total impedance change. Then the relation for M is

$$M = L_0 - L_S, \qquad (11)$$

where L_S represents leakage inductance proportional to the magnetic flux that does not pass through the winding of the second coil.

By replacing of air transformer with T-network we obtain the following simplification, Fig.5,

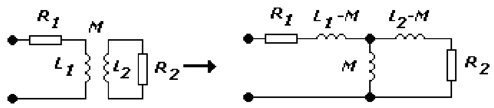

Fig.5: Equivalent circuit of T-network

then the total impedance of T-network can be expressed by the next formula

$$\dot{Z}_T = \left(R_1 + \frac{\omega^2 R_2 M^2}{R_2^2 + \omega^2 L_2^2}\right) + j\omega\left(\frac{L_1 R_2^2 + \omega^2 L_1 L_2^2 - \omega^2 L_2 M^2}{R_2^2 + \omega^2 L_2^2}\right), \qquad (12)$$

By neglecting of coil winding resistance R_1 and the leakage inductances L_1, L_2 and M and by replacing of secondary resistance of the coil it can be considered as an equivalent resistance of material under inspection normalized with respect to the primary side. The impedance obtain the form

$$\dot{Z}_T = \left(\frac{\omega^2 r L^2_0}{r^2 + \omega^2 L_0^2}\right) + j\omega\left(\frac{r^2 L_0}{r^2 + \omega^2 L_0^2}\right) = R + j\omega L\,, \qquad (13)$$

With such kind of simplification the inductance L_0 is unchanged because we use the same coil, but the equivalent resistance r closely related to originating eddy currents is changed. Its value depends on the coil position towards material, material shape and parameters. That means if the material object is not placed in the sufficient distance of the coil, the eddy currents are not created and the equivalent resistance r approaches to infinity. Then the impedance absolute value is maximum and it is an imaginary number. When the distance between coil and material decreases then decrease also the r value and impedance absolute value. If the eddy currents are generated in material, losses are presented by an increase of real impedance components.

In a real case the coupling is not ideal and L_S is not negligible, because L_S increases with increase of lift-off. Observing the changes there is possible to determine the type of changes of equivalent resistance, lift-off, or material parameters, [5].

3. HEART VALVE REPLACEMENT

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. Heart valves play a critical role in regulating blood flow through the cardiovascular system. Diseases of the heart valve can either be congenital or caused by infections such as rheumatic fever or endocarditis. The disease can lead to either stenosis, where the valve fails to open completely, or regurgitation, where the valve fails to close completely. In the instances where the damage cannot be repaired through surgery, replacement with a prosthetic device is often indicated. Special type of heart valve replacement widespread used in medical praxis is Bjork- Shiley- Convexo- Concave (BSCC).

The BSCC valve consists of a pyrolytic carbon disc that serves as an occluder to block the flow of blood in one direction but allows flow in the other direction. The valve employs two struts as shown in Fig. 6 to hold the disc in place. The outlet strut is welded to the suture ring while the inlet strut is integral to the ring. Although the exact reason has not been determined, a combination of circumstances including fatigue causes one of the welds, anchoring the outlet strut, to fracture. The failure of the other weld can cause a separation of the strut from the suture ring, thereby allowing the disc to detach from the valve. This can be dangerous and consequently there is a considerable interest to design such methods that can detect this separation.

Fig. 6: BSCC

4. DESCRIPTION OF SIMULATED PROBLEM

The defects that happen on the prosthetic heart valves most commonly affect the output strut that is stressed by occlusion disc movement. With regard to the available software limits the simulation proceeded in the following conditions.

For simulation we have selected the pancake coil type. This coil type is structurally simple and suitable for the defects detection of every orientation. The coil dimensions were selected with regard to the defect dimensions Fig.7. The excitation frequency of coil was 500 kHz.

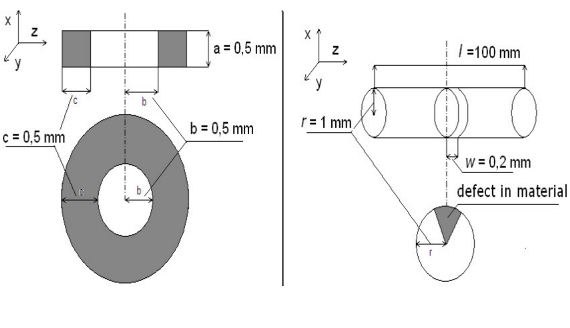

Fig. 7: Dimension of coil and material

The output strut of a heart valve replacement for which we realized the simulation of examination by eddy currents method we replaced by conductive material with dimensions adapted to the output strut dimensions and simulation needs. It helped us to obtain the simplified model suitable for available software. The electromagnetic parameters of selected conductive materials are the conductivity and the permeability corresponding to the metallic biomaterials used for the heart valves replacements, have the values relative permeability, $\mu_r = 1$ and the conductivity $\sigma = 1{,}4.10^6$ [S/m].

The materials commonly used for the conductive heart valves replacement are defined apart from their electric and magnetic properties also by parameters characterizing the materials e.g. strength, elasticity and chemical elements abundance. The biomaterials which are often used for production of artificial heart valves are the following metallic alloys:

- Stainless steels 316L
- Cobalt alloys F 75, F 90
- Titanium alloys Ti-6Al-4V

With respect to the used software limits the simulation proceeded in the following spatial configuration.

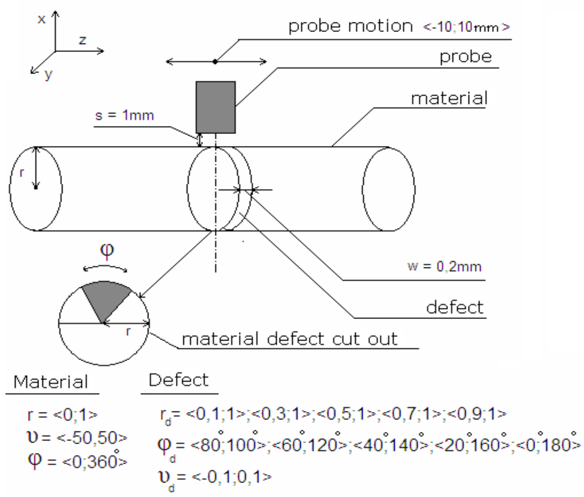

Fig. 8: Spatial configuration during evaluation using ECT

The coil with determined dimensions, Fig.8 was placed above a conductive material in the lift - off s= 1mm and it was moved in section <-10; 10> mm, because the defect was positioned in the middle of material, where z=0.

The defect width was w=0,2mm and the defect depth r were changed during inspection. The depth values are shown in the Fig.8, marked as r_d. The defect opening angle φ_D was changed simultaneously with the defect depth.

5. NUMERICAL SIMULATION RESULTS

The material object and the coil of given dimensions were used for numerical simulation of eddy current testing. The depth of defect changes simultaneously with opening angle of defect changing during simulation, which is represented by 25 performed simulations.

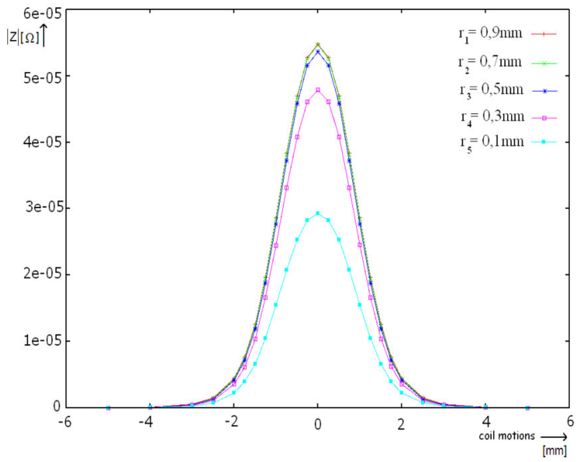

Fig. 9: The simulation result graphics presentation shows a relation of coil impedance change from its movement above the material, where φ = <40°; 140°>, and the defect depth r_1=0,9mm, r_2= 0,7mm, r_3=0,5mm, r_4=0,3mm, r_5= 0,1mm

From the final diagram Fig. 9, showing a relation of coil impedance change dependence on its movement above the given material it is possible to localize the defect in material. Five different curves represent five different depths of defect for one opening angle and the change of the coil impedance reacts to corresponding changes.

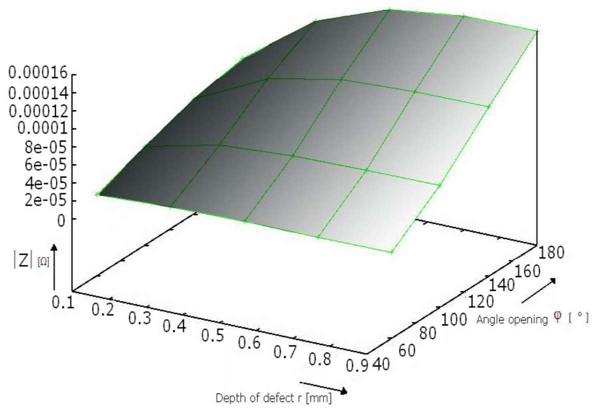

Fig. 10: 3D dimensional dependence of impedance change |Z| on the depth of defect r and defect opening angle φ

From the 3D diagram, Fig. 10, showing a relation of the impedance amplitude change dependence on the opening angle and defect depth we can see that with the increasing defect opening angle and depth of defect is increasing also the coil impedance amplitude. From the obtained graphic relations it is possible to say that the ETC method is sufficiently sensitive also to material defects with relatively small dimensions (tenths of millimeter) occurring in conductive heart valve replacements.
The higher accuracy of numerical simulations with regard to defect localization is possible to obtain by finer network density. Other parameter affecting accuracy is the coil driving signal frequency, where it is necessary to choose compromise between inversely proportional resolution and frequency.

6. CONCLUSION

A broad spectrum of NDT electromagnetic method applications in various industrial sectors led to exploring the possibilities for utilization of these methods also in medical praxis. The development of these methods, their application and optimizing of device components are studied in the meantime. But on the basis of these results the eddy currents method is quite suitable also for the defect detection in the heart valve replacements. A timely inspection of the output strut of the heart valve replacement „in vivo" would allow reduce a risk of rise damages because the prosthetic replacement defects could be incompatible with human health or even the human life

Acknowledgement

The work reported in this paper was supported by VEGA number 1/0308/08. The support is gratefully acknowledged.

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