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INFLUENCE OF SELECTED PARAMETERS ON DETECTION OF HEART VALVES OUTLET STRUT FRACTURES USING ECT METHOD

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***Abstract**: The Bjork-Shiley Convexo Concave (BSCC) mechanical heart valve has been used in surgery between 1979- 1986. It was one of the most prevalent mechanical heart valves in that period. The valve is however plagued by an increased occurrence of unexpected mechanical failures of its outlet strut compared to equivalent valve types, with a high incidence of mortality, when they occur. The periodic evaluation of the state of the BSCC valve, non-destructive test of each individual valve may help to detect the fractures presented in heart valve replacements and so prevent the damages of the valve. According to these facts this article presents one of the electromagnetic methods - eddy current testing for noninvasive inspection of BSCC valve integrity. Prior studies of eddy-current testing have shown that the detection capabilities of the method depend on various parameters. Influences of the lift-off and excitation frequency on detected signal originated from cracked outlet strut are investigated and presented. The first part of the article contains introduction of the problem and description of the defect that occurs in BSCC heart valve. Description of the simulated problem that was performed, obtained results and their interpretation in the medicine are presented in the second part of the article.*

Key words: *Bjork-Shiley prosthetic heart valves, material defect of outlet strut, eddy current testing, numerical simulations*

INTRODUCTION

The human heart can be considered as a twin positive displacement pump working in tandem for supporting the systemic and pulmonary circulation of blood. Each pump comprises of a receiving chamber called atrium and a pumping chamber called ventricle. Each ventricle has two valves, one each at the inlet and outlet to ensure the unidirectional flow of blood. The human heart valves could be affecting by two main types of diseases. The heart valves suffer from two main types of diseases. One of them is the narrowing of the aortic valve (Aortic Stenosis). When the degree of narrowing becomes significant enough to impede the flow of blood from the left ventricle to the arteries, heart problems develop. Another medical condition is one in which the valve doesn't close completely, causing backflow. This is called incompetence or regurgitation. If the application of the corrective action (such a medication therapy or reoperation) is not possible, one alternative is to replace the malfunctioning valves with prosthetic devices. Artificial heart valves are engineered devices which must be designed to survive more than 109 cycles over 40 years of operation. Thus, fatigue represents one of the primary driving forces for safe operation of these devices. The inability to maintain the long term performance of critical devices in the future may lead to catastrophic failure and patient's loss of life. Two types of artificial heart valves are mainly used today: mechanical heart valves and biological valves.

One type of mechanical valve called the Bjork Shiley Convexo Concave (BSCC) heart valve was widely implanted between 1979 and 1986. The BSCC heart valve is a mechanical prosthetic heart valve that is famous not for an excellent design but for a history of failure. Of the 86,000 patients who received these valves, four hundred died from a strut fracture, in the first year. Two hundred additional patients survived similar strut fractures through open-heart surgery, [3].

These valves have a carbon occluder disc held in place by two metallic struts. Of the two struts, the inlet strut is integral to the valve suture ring, while the other strut called the outlet strut is welded to the suture ring. Fig.1, shows a typical BSCC heart valve.

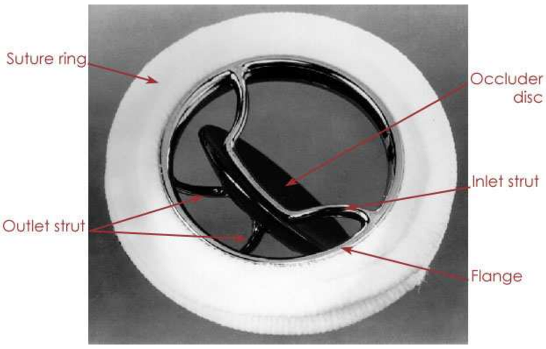

Fig. 1: Typical heart valve BCSS, photograph of entire devices, where the occluder disc and the minor struts are clearly visible

In rare instances, fatigue and other factors caused by cyclical stresses cause the fractures of welds at one of the ends. Such a condition is called as Single Leg Separation (SLS). Although the function of the valve can continue under these conditions, it increases the stress concentration on the intact end of the welded strut and it is uncertain how long the other end of the strut can remain intact. Fig. 2 shows result of electron microscopy scan of a leg fracture, [1].

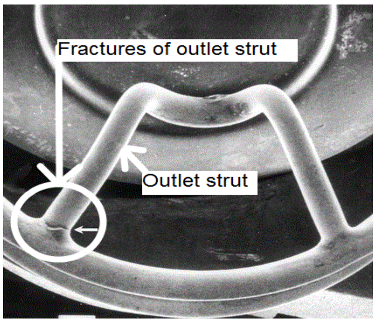

Fig.2: Fracture of outlet strut

Fracture at both ends will cause detachment of the disc from the rest of the valve, leading, in almost all cases, to fatality. There is considerable interest, therefore, in the development of methods for assessing the state of the valve in general and the condition of the outlet strut weld. The present paper presents use of electromagnetic field for this purpose. Eddy current testing is an electromagnetic method for non- destructive examination of the outlet strut of BSCC heart valves. The principal difficulty with generating electromagnetic effect in a biological environment is that blood and live tissue are highly dispersive, and, therefore extremely lossy. This means that any measurements will definitely have to be invasive, e.g., via catheter. Even in such circumstances, it seems doubtful whether a significant electromagnetic effect can be generated and measured. To investigate this, it was decided to realize it with the aid of numerical simulation techniques.

Numerical simulations based on the finite element method are carried out to investigate capabilities of the ECT in the strut inspection. Influences of several variables on a detected signal due to a crack are studied.

1 EDDY CURRENT TESTING (ECT)

Non-destructive testing (NDT) for conductive materials requires high reliability to detect cracks and defects in advance. Eddy Current Testing (ECT) is one of the non-destructive techniques often used to detect them. In this method, a frequency dependent exciting current is commonly used to measure voltage changes on the pick-up coils for high detection sensitivity. It changes the magnetic field around conductive objects where cracks and defects (or variations in electrical conductivity, magnetic permeability, lift-off) prevent the flow of the eddy currents, and thus leading to changes of the impedance of the pick-up coil, Fig.3. In order to detect the defects sensitively, high frequency exciting currents or appropriate lift - off have to be applied. This method is applicable for surface or subsurface flaw detection because of significant decrease in magnetic flux and eddy current density with depth. The depth of penetration of eddy current is limited by skin-effect, which depends on operating frequency, material conductivity, and permeability, [2].

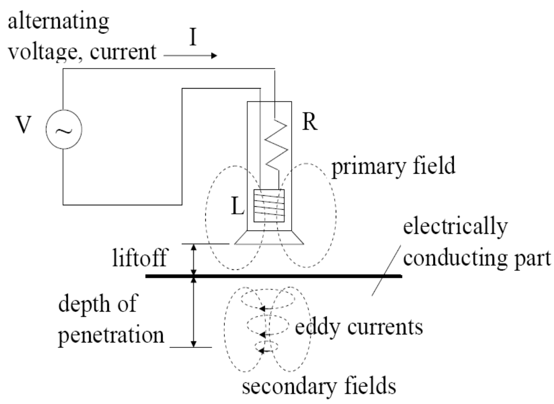

Fig.3: Basic principle of ECT measurement

1.1 *Electromagnetic field equations*

ECT is modelled using the quasi-stationary approach. Usually, this approach gives reliable results when the time changes of EM field are relatively slow, so the displacement current can be neglected ($\mathbf{J} >> \mathbf{D}/t$). EM field in conductive materials fulfills this condition also at higher frequency range because the conductive current is much higher than the displacement current.

The quasi-stationary EM field is described by the four Maxwell’s equations in the following form:

$$\operatorname{rot}\mathbf{H} = \mathbf{J}\,, \quad (1) \qquad \operatorname{rot}\mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}\,, \quad (2)$$

$$\operatorname{div}\mathbf{B} = 0\,, \quad (3) \qquad \operatorname{div}\mathbf{D} = \rho_0\,, \quad (4)$$

where: **H** [A.m^{-1}] is the magnetic intensity vector, **E** [V.m^{-1}] is the electric intensity vector, **B** [T] is the magnetic flux density vector, **D** [C.m^{-2}] is the electric displacement vector, **J** [A.m^{-2}] is the conducting current density vector and ρ_0 [C.m^{-3}] is the volume density of free charges. The materials’ relations between the vectors of EM field are:

$\mathbf{D} = \varepsilon\, \mathbf{E}$, (5) $\mathbf{B} = \mu\, \mathbf{H}$, (6) $\mathbf{J} = \sigma\, \mathbf{E}$, (7)

where ε [Fm^{-1}] is permittivity, μ [$H.m^{-1}$] is permeability and σ [$S.m^{-1}$] is conductivity of a material.

The EM field can be analyzed using the potential functions:

$$\mathbf{B} = \mathrm{rot}\mathbf{A}, \quad (8) \qquad \mathrm{grad}\, V = -\mathbf{E} - \frac{\partial \mathbf{A}}{\partial t}, \quad (9)$$

$$\mathrm{div}\mathbf{A} = 0, \quad (10)$$

where **A** [T.m] is the magnetic vector potential and *V* [V] is the electric scalar potential. The ECT analysis is conducted by magnetic vector potential **A** and electric scalar potential *V*. Fig.4 shows a configuration for typical eddy current problems.

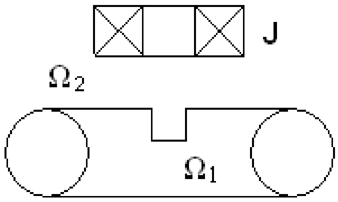

Fig.4: Typical configuration of ECT

The solution domain is subdivided into conducting area Ω_1 and non-conducting area Ω_2. The eddy current in conductor is governed by following equations:

in air region: $$\nabla^2 \mathbf{A} = 0 \quad (11)$$

in coil region: $$\nabla^2 \mathbf{A} = -\mu \mathbf{J} \quad (12)$$

in conductor region: $$\nabla . \sigma\left(-\nabla V - \mathrm{j}\omega \mathbf{A}\right) = 0 \quad (13)$$

$$\nabla^2 \mathbf{A} - \mathrm{j}\omega \mathbf{A} - \mu\sigma \nabla V = 0 \quad (14)$$

By solving this set of equations we get **A** and *V*. Then the induced voltage in the pickup coil was counting and the impedance of the pickup coil were obtained.

1.2 Numerical evaluation - Model Configuration

The problem deals with absolute coil type, placed above an outlet strut of BSCC heart valve replacement. The probe coil with dimensions, Fig.5, has axis-symmetric shape and has 10 turns. It is supplied with current density **J=** 1A/mm^2. Simulations were performed with various settings of lift - off s_1 =1mm, s_2= 2mm, s_3= 3mm, s_4 =5mm (analogy to real motion of outlet strut in the real human body). Frequency of the driving harmonic coil signal was also changed. The simulations were performed for following frequencies f_1= 10kHz, f_2= 20kHz, f_3 = 30kHz, f_4= 50kHz, f_5= 100kHz, f_6 = 200kHz, f_7= 500kHz. Various frequencies were used for demonstration of crack sensitivity influence.

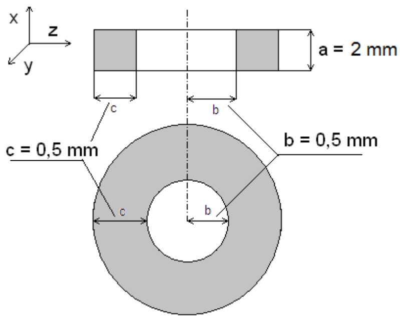

Fig.5: Dimension of the absolute coil

Properties of the investigated material, dimensions and electromagnetic parameters of the heart valve replacement were set according to real dimensions and electromagnetic parameters of the heart valve replacements. The materials commonly used for the conductive heart valves replacement are Stainless steel 316L, CoCr -F 75,F 90 alloys and Titanium alloy -Ti-6Al-4V. For our simulation the BSCC heart valve was made from titanium alloy Ti-6Al-4V thus the conductivity was σ = 1,4.10^6 [S/m] and relative permeability μ_r = 1.

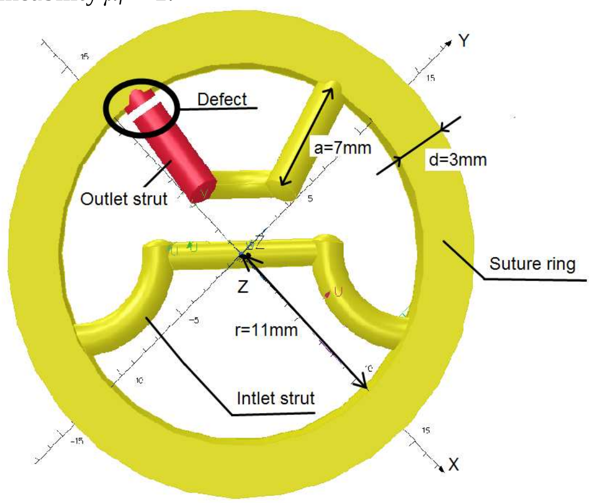

Fig.6. Dimensions of heart valve with defect localized on the outlet strut

The defect was localized on the one end of the outlet strut, Fig.6. The defect width was *w*=0.1mm, the defect depths were changed during inspection. The depths of defect were following r_1 =0,1mm, r_2 =0,3mm, r_3 =0,5mm r_4 =0,7mm, r_5= 0,9mm. Material defect has no conductivity σ = 0 [S/m]. The dimensions, orientation and depth of the defect were set up according to real dimensions and depth of defect that affects outlet strut of BSCC heart valve. Such types of the defect can be presented as fatigue cracks.

The solution of the forward problem requires the determination of the impedance change of the probe. This parameter was evaluated by subtracting the values obtained from the material without defect from the values obtained for the material with defect.

2 Numerical simulation results

The material object (BSCC heart valve) and the coil with given dimensions were used for numerical simulation of eddy current evaluation. The depth of defect, lift-off and frequency of the driving signal were changed during the simulations. It represents 32 simulations performed. The numerical simulation were performed in Finite element code in software for electromagnetic modeling.

The graphs Fig.7,8 were performed with lift-off s_1= 1mm and f_4=50kHz (the frequency 50kHz were chosen regarding to [2]) and the depths of defect were changed r_1, r_2, r_3, r_4, r_5 (as was mentioned in the previous chapter).

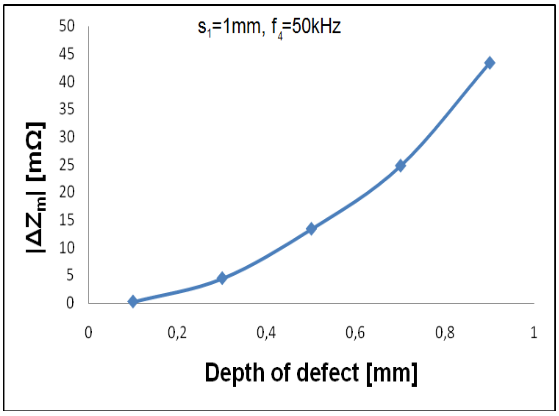

Fig.7: Dependence of maximum impedance module on defect depth

From the obtained results in graphic form, Fig.7, showing a dependence of maximum impedance module $|\Delta Z_m|$ on defect depth we can see that with increasing of depth of defect also the maximum impedance module is rising. From the different values of the $|\Delta Z_m|$ it is possible to determine the depth of defect. The waveform points for individual depths of defects are well-separated.

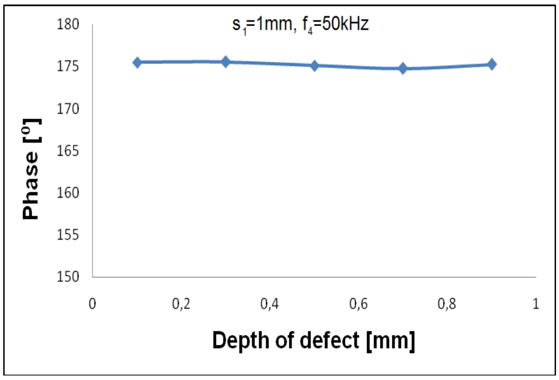

Fig.8: Dependence of maximum impedance phase on defect depth

Fig.8, shows a graphical dependence of the maximum impedance phase on defect depth, it is possible to see that the different type of defect depth doesn't influence a phase of a resulting signal. Almost the same result (waveform) represents the Fig.10, where the different values of frequency do not influence a phase of the resulting signal. It means that defect depth and frequency of the driving signal do not influence so markedly the phase of response signal.

The next two graphs, Fig.9,10, were performed with lift-off s =1mm, the depth of defect r_3 =0,5mm and the frequency was changed f_1, f_2, f_3, f_4, f_5, f_6, f_7 (as was mentioned in the previous chapter).

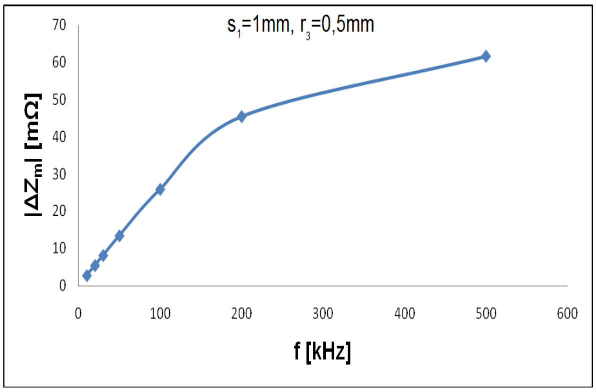

Fig.9: Dependence of maximum impedance module on given frequency

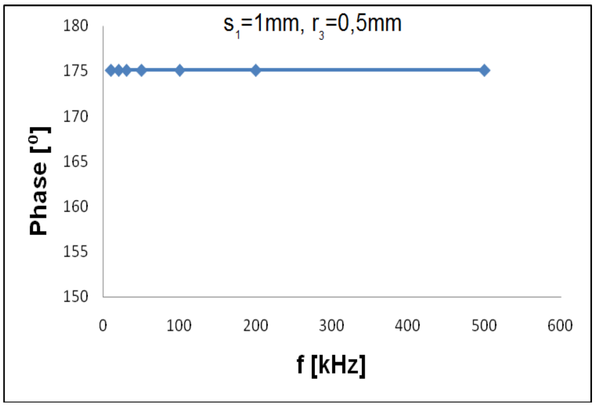

Fig.10: Dependence of maximum impedance phase on given frequency

The following obtained results, Fig.11,12, were performed with depth of defect r_3= 0,5mm, exciting frequency f_4=50kHz and the lift- off was changed s_1=1mm, s_2=2mm, s_3=3mm, s_4=5mm.

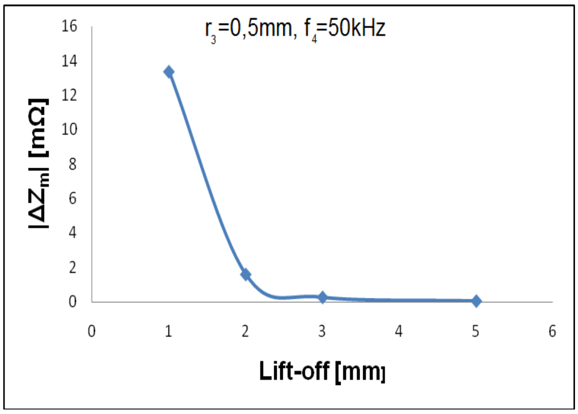

Fig.11: Dependence of maximum impedance module on lift-off

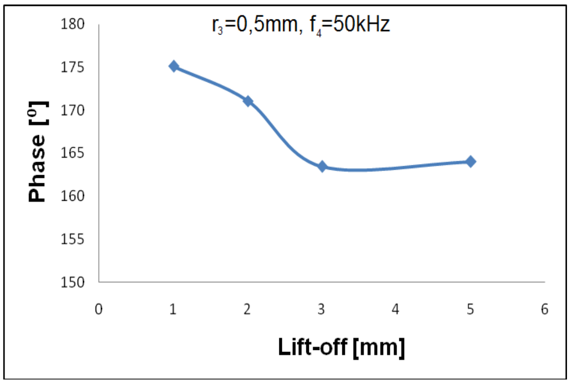

Fig.12: Dependence of maximum impedance phase on lift-off

As can be seen, from the Fig.11 with increasing lift-off the $|\Delta Z_m|$ is decreasing. From the waveform it is evident that the $|\Delta Z_m|$ fall to zero-value. From these results it is possible to determine the lift-off value which is necessary for the sufficient information value of the detected signal. While the frequency variations and the defect depth variations do not influence the phase response signal, the lift-off changes influence the phase response signal markedly.

3 Conclusion

Eddy current testing method has been presented for surface and sub-surface cracks detection in conductive materials in the paper. Material defects that can be present at BSCC prosthetic replacement have been simulated and discussed. Various parameters changes such as lift-off, depth of the defect and frequency of the driving coil on signal variations have been inspected and analyzed regarding to coil impedance changes. Numerical simulations results represent that the deeper is the material defect the greater is the amplitude of the coil impedance change and this dependence increases exponentially. Saturation of the coil impedance change signal is observed, when increasing frequency of the driving signal. Value of lift-off parameter is indirectly proportional to the coil impedance change. Due to this facts can be said that ECT method can be used to inspect such types of material defects that occur in prosthetic heart replacements of BSCC heart valve, too. This method allows inspection in vitro as well as in vivo environment.

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