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Single leg fracture in artificial heart valve - electromagnetic detection of impedance changes

***Abstract**. Björk Shiley Convexo Concave (BSCC) heart valve is a special type of the mechanical heart valve which was implanted to many patients worldwide. In some cases, for reason yet unclear the outlet strut - weld fractured after several years of use. This type of fracture usually causes a malfunction of the valve what is incompatible with further life. For this reason a new approach for the inspection is proposed based on sweep frequency eddy current testing. Standard self inductance pancake probe drives the eddy currents and pick-ups the response signals. Numerical simulations and experimental measurement are carried out to evaluate the proposed technique. The gained results presented in the paper show that there is an evident difference in the amplitude frequency spectrum of the response signal between the intact valve and the one with a single leg fracture of the outlet strut.*

***Streszczenie.** Zastawka Björk-Shiley'a (BSCC) to mechaniczny implant zastawki serca, masowo stosowany na całym świecie. W niektórych zastawkach z nieznanego dotychczas powodu dochodzi po kilku latach od operacji do pęknięcia zewnętrznego wspornika zaworu. Ten rodzaj uszkodzenia powoduje zazwyczaj wadliwe funkcjonowanie zastawki. W artykule zaproponowano nowe podejście do inspekcji kondycji zastawki z wykorzystaniem testowania nieniszczącego przy pomocy prądów wirowych z przemiataniem częstotliwości. W celu oceny zaproponowanej metody wykonano symulacje numeryczne i pomiary eksperymentalne. Rezultaty zaprezentowane w artykule pokazują wyraźną różnicę w odbieranych sygnałach pomiędzy sprawną zastawką, a zastawką z uszkodzonym pojedynczym ramieniem wspornika. **(Elektromagnetyczna detekcja pęknięcia ramienia wspornika w sztucznej zastawce serca)**x*

Keywords: eddy currents, sweep frequency technique, prosthetic heart valve, single leg fracture, intact outlet strut.
Słowa kluczowe: testowanie nieniszczące, technika przemiatania częstotliwości, sztuczna zastawka serca, uszkodzenie zaworu.

Introduction

Dysfunction of the heart valves is a common complication after heart valve diseases (aortic stenosis, incompetence or regurgitation). If the medication therapy is not successful the artificial heart valve is used to replace the malfunction heart valve. One special type of mechanical heart valve prostheses is a Bjőrk-Shiley Convexo Concave (BSCC) heart valve which was introduced in 1979. BSCC heart valve has been used to replace the aortic or mitral valves and the design was developed in order to improve the hemodynamics and reduce the risk of thromboembolism. The BSCC valves have a carbon occluder disc held in a 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 the BSCC heart valve.

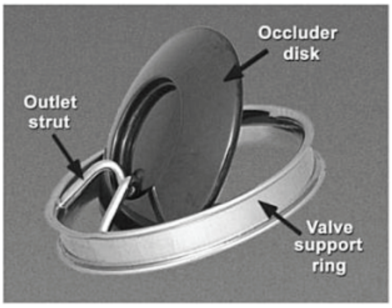

Fig.1. Typical design of the BSCC heart valve

Furthermore, the process of cyclic slamming open and shut of the occluder disc during heart function subjects the valve percussive impact stress which can cause fatigue failure. These failures have been observed at the outlet strut flange junction near or at the weld. The failure of the both struts causes dislodgement of the occluder disc and embolization of the disc. A dual strut failure results in abrut onset of dyspnea, loss of consciousness, or cardiovascular collapse due to embolization of the disc and acute severe valvular regurgitation. During the eight years that the valve was on the market, approximately 86000 valves were implanted in patient. Six hundred and fifty valves experienced outlet strut fractures, [1]. Due to this fact there is a considerable interest, therefore, in development of methods for assessing the state of the valve in general conditions of the outlet strut weld by minimally invasive non-destructive inspection method. Electromagnetic methods represent a good candidate, [2].

Eddy current non-destructive testing is widely utilized in a variety of industrial applications. An eddy current probe scans over an inspected surface and the response signals are evaluated accordingly. However, the conditions of considered application do not allow such scanning.

A new approach using eddy current technique for the non-destructive testing of BSCC is proposed in the paper. It is based on sweep frequency inspection. Numerical simulations and experimental measurements are carried out and gained results are presented and discussed in this paper.

Electromagnetic method - Eddy current testing (ECT)

One of the widely utilized electromagnetic methods is the eddy current testing (ECT). 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, [3]. The method is especially suitable for detection of surface and near surface defect. The main advantage of ECT is its high sensitivity to small and shallow defects that occur in a prosthetic replacement. The ECT method is applicable only for conductive materials but it doesn't represents a problem for this application because the BSCC heart valve is made from metallic biomaterials (Stainless steel, CoCr alloys and Titanium alloy). The conditions and implements of ECT make this method convenient for the detection of defects, which usually affect the conductive prosthetic replacements.

Numerical model

Possibilities of sweep frequency eddy current inspection of BSCC are investigated in the paper using numerical means. The commercially available software OPERA-3D based on finite element method is utilized for the purpose.

Standard self-inductance pancake probe, shown in Fig. 2, is used for the inspection. The dimensions of the probe are set up according to dimensions of the heart valve. The dimensions of the catheter which would be used for encapsulations of the coil are considered, as well. The probe is positioned 1 mm above the weld of the oultet strut where a crack is considered to appear. Current density of the exciting signal is kept constant during the inspection at a value of J = 1 A/mm^2, while its frequency is changed in a wide range starting from 10 kHz up to 500 kHz.

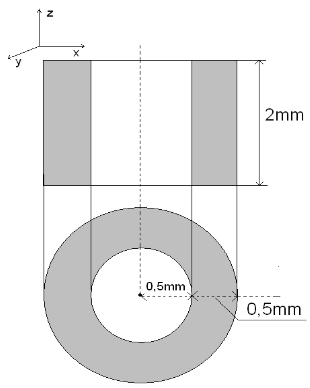

Fig. 2. Dimensions of the pancake probe.

The complex model of the BSCC is developed. The dimensions and electromagnetic properties of the model are adjusted according to real dimensions and material properties of the BSCC heart valve. The dimensions of the heart valve are shown in Fig.3. The materials commonly used for the BSCC heart valve replacement are Stainless steel, Titanium alloy and Co-Cr alloy. The developed model considers the electromagnetic parameters of the Co-Cr alloy (Hayness 25), the conductivity is adjusted to $\sigma = 1.14 \cdot 10^6$ S/m and the relative permeability to $\mu_r = 1$.

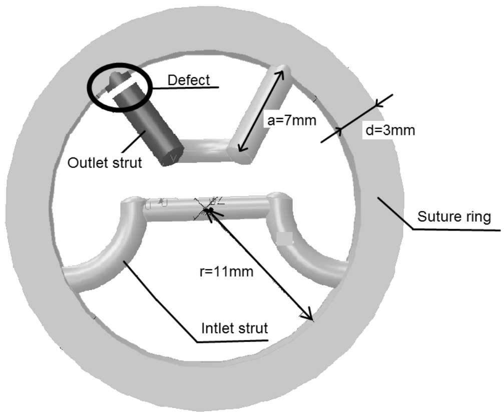

Fig. 3. Dimensions of the BSCC heart valve model.

Considered defect is localized at one end of the outlet strut, Fig.3. The defect is non-conductive, i.e. fatigue crack, and it represents single leg fracture (SLF) of the BSCC. Dimensions, orientation and depth of the defect are adjusted according to real conditions that may appear in the outlet strut of BSCC heart valve. Width of the modelled defect is set to w = 0.1 mm and its depth d is varied from 0.1 up to 1.9 mm with a step of 0.2 mm. The simulations are run for the intact outlet strut (IOS) as well for the comparison.

Numerical simulations using the developed model are carried out to calculate the probe response signal. The following section presents the results.

Numerical simulations results

Results of the numerical simulations of the model introduced above are presented in this section. Fig. 4 shows amplitude frequency spectrum of the probe response signal in absolute values for four cases. The curve denoted as IOS represents the sweep frequency response signal dependence for the intact outlet strut. The other three dependences are for the single leg fracture (SLF) with different depth of the defect, i.e. 0.1 mm, 0.5 mm and 1.9 mm. The inductive component is dominant in the probe response signal and thus the phase frequency spectrum does not show almost any difference between the IOS and the SLF.

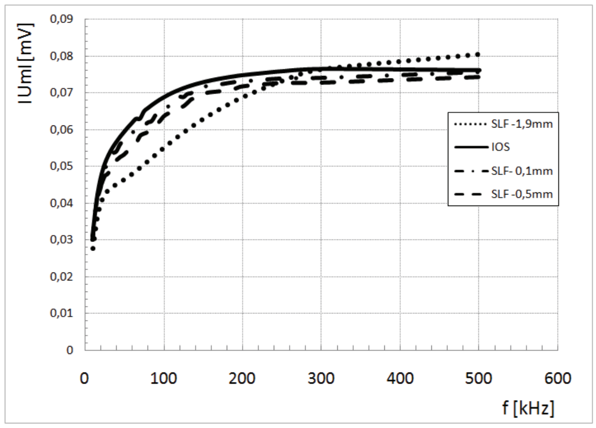

Fig. 4. Amplitude frequency spectrum of the probe response signal in absolute values

It is evident from the presented results that there is a clear difference in the amplitude frequency spectrum between the IOS and SLF. It should be noted that the difference is more notable when the depth of defect is increasing. The difference in dependences between IOS and SLF is highest one in a frequency range from 70 kHz up to 150 kHz.

Experimental measurement - system components

For the experimental measurement was used the prototype of the BSCC heart valve which was made from CoCr alloy type Hayness 25. One prototype of the valve was without defect (intact outlet strut - IOS) and other prototype of the valve contains the defect on the one end of the outlet strut, Fig.5. The depth of the defect was d = 0,6mm.

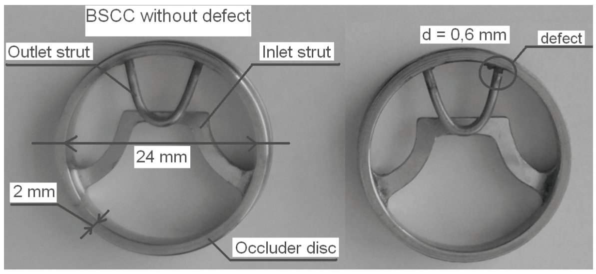

Fig. 5. Prototype of the BSCC heart valve with defect

For the measurement was used the eddy current testing probe with coil parameters L=351µH and has N=600 turns. The probe was positioned above the outlet strut with defect, in proximity s = 1mm, Fig.6. The reference signal represent the signal from BSCC heart valve without defect (IOS). The signal from BSCC heart valve with defect is called as a single leg fracture – SLF.

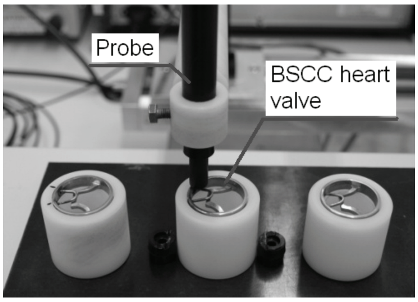

Fig. 6. Orientation of the probe and prototype of the valve

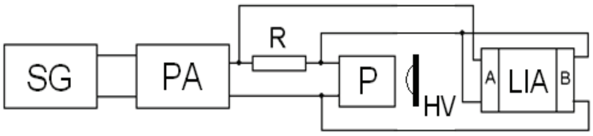

Fig. 7. The system block diagram of the measurement

Fig. 7. shows a block diagram of the measurement, where SG - signal generator, PA - power amplifier, P - probe, R=0,5Ω, HV - prototype of the heart valve, LIA - Lock in amplifier with two channels A and B. The signal generator produces the excitation waveform which is amplified to drive the excitation coil. The probe generates a magnetic field around the heart valve during the test.

Experimental results

The results shows that the detected signal is different for the IOS and SLF valve, because of different eddy current flow. This demonstrates that a SLF can be detected by measuring detected signal variation in dependence on frequency. It can be concluded that the sweep frequency technique proposed for eddy current inspection of BSCC outlet strut is very promising. It helps to overcome one problem connected with eddy current inspection concerning the given condition. Scanning over an inspected surface is not needed.

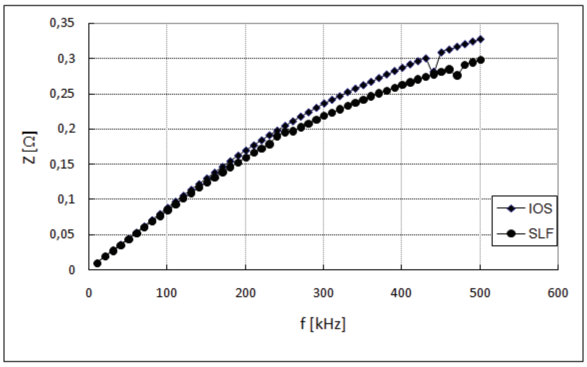

Fig. 8. Dependence of impedance on frequency

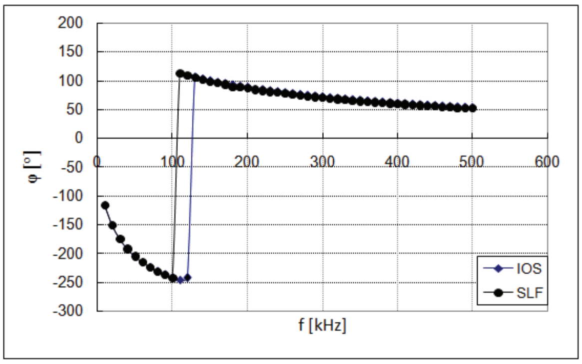

Fig.9. Dependence of impedance phase on frequency

Conclusion

The paper introduced a new approach for defect detection in Björk Shiley Convexo Concave artificial heart valve using sweep frequency technique. This method detects perturbations in eddy current flow due to a defect in the outlet strut in a wide frequency range. A model of the valve was developed and proposed technique was verified using numerical simulations. The presented results from the numerical simulations and experiment clearly showed that there is a perceivable difference in amplitude frequency spectrum between the intact outlet strut and the strut with defect.

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