

# NON-DESTRUCTIVE TESTING OF ARTIFICIAL JOINTS WITH DEFECTS BY EDDY CURRENT METHOD

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## Abstract

*This work deals with non-destructive testing of artificial joints made from the austenitic steel SUS316L based on eddy current method. The technique is appropriate for final investigation of artificial joints before insertion the prosthesis into human body to avoid repeated operations. The most commonly implanted joints - knee and hip joint are evaluated in this study. The eddy current probe consists of one coil, which has both the excitation and sensing functions. Five defects are inspected using three different frequencies. The numerical simulations from Opera software with experiments are compared in this article to obtain the most appropriate frequency. The aim of this work is evaluation which frequency provides the biggest magnitude difference between individual simulated signals with various depths if surface defects are inspected.*

## Keywords

*artificial joints, austenitic steel, non-destructive testing, eddy currents*

## Introduction

Nowadays, the investigation of artificial prostheses is very significant field. Non-destructive method is type of technique which evaluates an object without damaging it. Eddy current testing is one of the electromagnetic methods which is useful for testing of biomaterials with nonzero conductivity. This method successfully detects the defects inside an inspected product. The value of testing frequency depends on the type of a detected defect (surface or subsurface). This work concerns on a reliable frequency selection for detection of surface defects using probe of absolute type, it means the eddy currents are excited and sensed by a same coil. This probe continuously moves over a tested material containing defects and resulting signal is displayed.

In the world there are a lot of repeated operations of artificial prostheses. In Slovakia, the number of above mentioned operations represents around four hundred of hip joint and one hundred of knee joint. One of the reasons of the repeated operations may be inserting a damaged implant. Therefore, the artificial joints should be investigated before implantation and the eddy current method is suitable for it, [1].

## Artificial prostheses of joints

The endoprosthesis is the term used to describe the artificial joint intended to implantation. The hip and knee joints are the most often implanted types of artificial joints. The materials which are used to manufacture them must be non-toxic, non-carcinogenic, corrosion resistant and therefore they must meet the requirements of biocompatibility. Consequently the stainless steel, cobalt alloys, titan and its alloys are suitable for the purpose. The lifetime of the artificial joints depends on several factors, for example a patient weight or too big load in some sports. Then the exchange of endoprosthesis is essential, [2], [3].

## Non-destructive testing of materials

Non-destructive testing of material is included among the successful diagnostic methods. The test measurements are created by manual testing or using automated systems. The task of evaluation are the selection of damaged products, specifying of the

character and size of defects, their location and eventually making decision about the applicability of an object, [4].

The visual, penetrant, magnetic particle, ultrasonic, radiographic, potential drop method and eddy current method belong to the methods of nondestructive testing, [5].

### Eddy current method

Eddy current method is based on the phenomenon of electromagnetic induction and therefore it belongs to the electromagnetic methods of non-destructive testing. If a conductor is situated in a time-varying magnetic field, electromagnetic induction arises and it results in the induction of electrical voltage within the mentioned conductor. Currents are induced in planes, which are perpendicular to the vector of the magnetic induction. The shape of these currents resemble the whirlpool, consequently they are called eddy currents, [6], [7].

The coil is supplied with a time-varying electrical current and generates a time-varying electromagnetic field. If a conductive object is situated in the vicinity of the coil it causes the induction of alternating voltage and the flow of eddy currents is formed in the object. The direction of EM field of coil is opposite as the direction of electromagnetic field of eddy currents. The resulting field of this system is the connection of mentioned fields. Defects in the evaluated object impact the resulting electromagnetic field and cause a change of induced voltage in the coil. These changes give information about a presence of crack in a test material with nonzero conductivity, [6], [7].

The objective of eddy current testing (ECT) is to record the signal of the coil, which moves above surface of a material and evaluate whether the object contains a defect, [6].

### Numerical simulations and experiments by means of ECT

The purpose is to simulate the process of non-destructive testing by eddy current method. Numerical simulation of artificial knee and hip joint with various defects are made in the Opera software. Shape of nonconductive defects is rectangular. Results of these simulations are verified experimentally on the material SUS316L with the same properties.

#### Numerical simulation

The OPERA simulation package is based on the finite element method (FEM) and it is employed for simulations of electromagnetic field issues. The created models represent the artificial joints and contained defects are modeled in said software. The conductivity of the plate made of austenitic steel SUS316L is  $\sigma = 1.4 \times 10^6$  S/m and conductivity of the defect is  $\sigma_d = 0$ .

Dimension of prostheses models and location of defects are created on the basis of real implants.

All simulations are carried out by absolute type probe, which is positioned axially perpendicular to the material at a distance of  $h = 0.5$  mm. The both mentioned joints contain five surface defects with the same thickness  $w = 0.2$  mm and width  $l = 10$  mm. The depth is different for each defect. Depth of defects in the knee joint (Fig. 1) are  $d = 1, 3, 5, 7, 10.5$  mm and those in the hip joint are 1, 2, 3, 4 and 5mm deep.



Fig. 1: Evaluated knee joint and positioning of the probe.

The probe is positioned over intact place, meaning without defect to obtain reference value at first. Subsequently the probe movement over investigated material is defined over a distance  $\langle -10 \text{ mm}; 10 \text{ mm} \rangle$ , hence 21 numerical models are created for the hip joint. In the knee joint, there are made 31 numerical models in the range  $\langle -15 \text{ mm}; 15 \text{ mm} \rangle$ . The position "0" represents to the centre of defect.

The measurements are performed by three various frequencies  $f = 1 \text{ kHz}, 20 \text{ kHz}$  and  $100 \text{ kHz}$ . The frequency displaying the biggest magnitude difference between individual simulated depth signals is selected.

The simulations are created with the same mesh resolution in order to be able to compare results and to get on for the least possible error rate. The mesh of part of hip joint is shown in Fig. 2 and knee joint is displayed in Fig. 3.

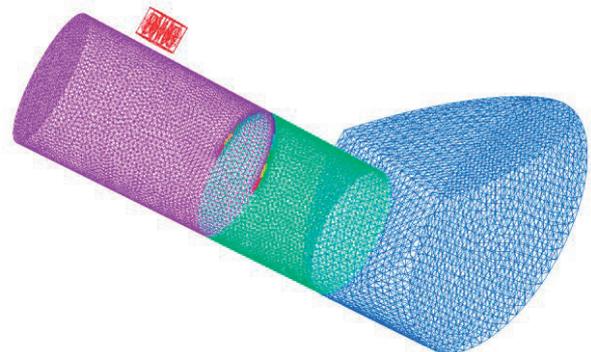


Fig. 2: The used mesh of hip joint.



Fig. 3: The mesh of knee joint.

### Experimental verification

The results of knee joint are verified by commercial eddy current equipment ELOTEST B300 manufactured by Rohmann and LOCK-IN amplifier.

The experiments are carried out using a plate made of austenitic steel contained artificial electro-discharge machined (EDM) slits. The dimensions of this plate are the following: length  $l_p = 0.12$  m, width  $w_p = 0.5$  mm and height  $h_p = 0.01$  mm.

Depths of defects are  $d = 1, 3, 5, 7$  and  $9$  mm. Other parameters, meaning conductivity of material and defects, thickness and width of defects and used frequencies are same as in the numerical simulations. The distance between individual defects is  $0.06$  m, so there is no overlap between resulting signals of neighboring cracks.

A 3-axis manipulator controlled by a PC, with an accuracy of  $10^{-6}$  m is used for precise regulation of the probe movement. The measurement probe of absolute type is located over the individual defects. The distance from the inspected object is  $h = 0.5$  mm due to encapsulation of probe. This probe is moved by the manipulator fluently from the place with the shallowest defect towards the deepest defect and the measurement is repeated for the three frequencies  $f = 1$  kHz,  $20$  kHz and  $100$  kHz.

The probe is fed with harmonic voltage generator and output signal is obtained using Lock-in amplifier and evaluated parameter is the voltage output of magnetic sensor. Lock-in amplifier in the realization of experiments serves as a filtering element whose aim is to filter out all signals barring the signal with a frequency that is probed supplied.

## Results

Results of the numerical simulations and experiments for artificial prostheses by three exciting frequencies are

compared. It can be concluded that the measurements made by numerical simulations are able to detect these surface defects using all the three frequencies. In fact, the experimental detection is successful only with the highest frequency applied. All results are viewed for the highest of the applied frequencies, therefore  $f = 100$  kHz.

### Results of numerical simulations

The real and imaginary values of magnetic flux density are obtained from Opera software. Consequently, the dependence of magnetic flux density on the probe position is created by them. In Fig. 4 and Fig. 5 it is shown mentioned dependences of five different defects.  $B_{\text{mod}}$  is module of magnetic flux density and the following expression can be used:

$$B_{\text{mod}} = \sqrt{\text{Re}\{B_z\}^2 + \text{Im}\{B_z\}^2} \quad (1)$$

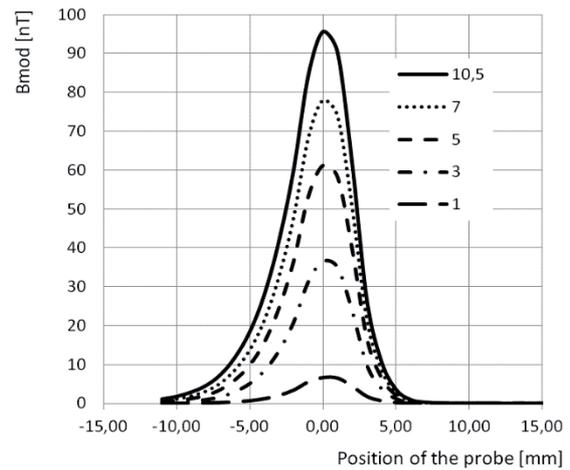


Fig. 4: Dependence of magnetic flux density on the probe position  $\langle -15 \text{ mm}, 15 \text{ mm} \rangle$  for the knee joint.

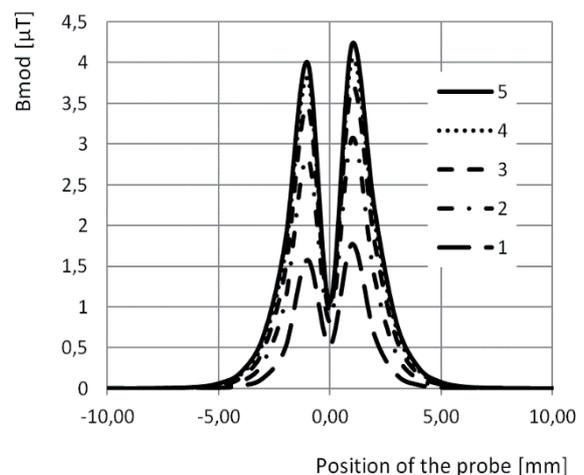


Fig. 5: Dependence of magnetic flux density on the probe position  $\langle -10 \text{ mm}, 10 \text{ mm} \rangle$  for the hip joint.

Fig. 4 displays the results of numerical simulations of the knee joint with depth of the defect  $d = 1, 3, 5, 7$  and  $10.5$  mm. Fig. 5 shows the numerical simulation results of the hip joint with defect depth  $d = 1, 2, 3, 4$  and  $5$  mm.

The both graphs displayed the smallest deflection when the defect with depth  $d = 1$  mm and conversely the biggest deflection represents the deepest defect.

### Experimental results

The results from commercial eddy current equipment are displayed in Fig. 6 and Fig. 7, which represent complex plane display and probe position signal dependences. Three frequencies are used in this study but only frequency of  $f = 100$  kHz detects all defects and it displays them as five different defects. In the Fig. 6 it is displayed the result of detection with frequency of  $f = 1$  kHz, for comparison. This frequency can not to detect any defects and it is not able to trace that measurement is made for five different defects. Therefore, it can be concluded that these types of defects are not possible to detect by the smallest used frequency.



Fig. 6: Dependence of differential response signal on probe movement for  $f = 100$  kHz.

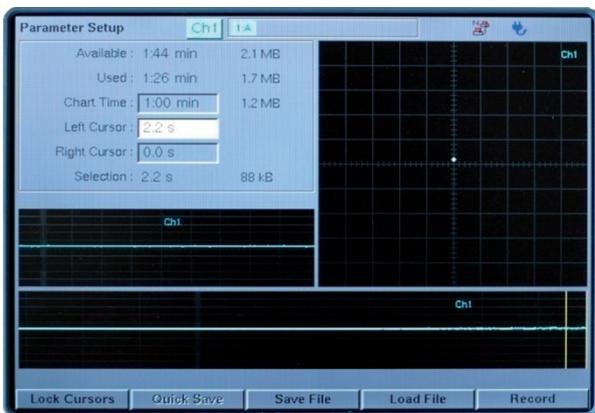


Fig. 7: Dependence of differential response signal on probe movement for  $f = 1$  kHz.

Next experiments are designed for comparison the results obtained. The results of measurement by Lock-in amplifier are displayed in Fig. 8 and Fig. 9. These results confirm that the frequency  $f = 100$  kHz is suitably selected and the smallest frequency is not usable.

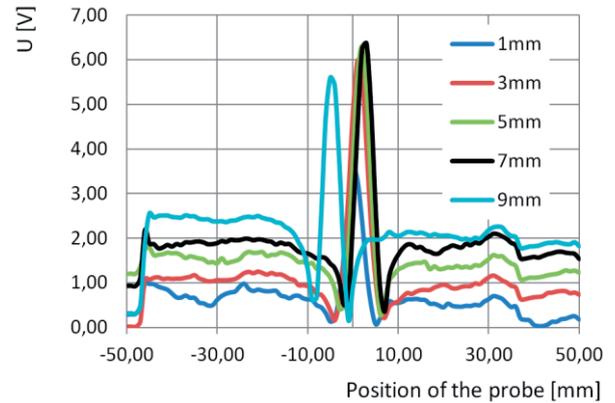


Fig. 8: Dependence of the voltage output of magnetic sensor and probe position  $\langle -50\text{mm}; 50\text{mm} \rangle$  at a frequency  $f = 100$  kHz.

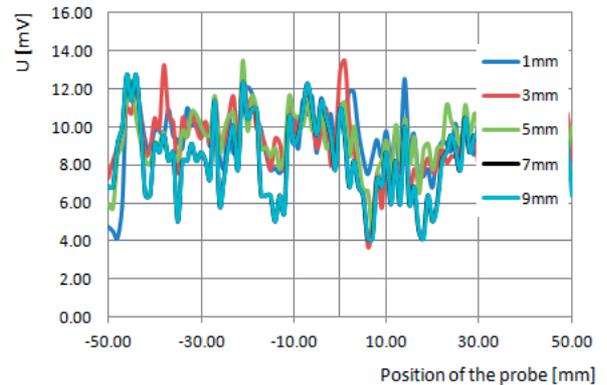


Fig. 9: Dependence of the voltage output of magnetic sensor and probe position  $\langle -50\text{mm}; 50\text{mm} \rangle$  at a frequency  $f = 1$  kHz.

### Conclusion

Eddy current testing is powerful tool for evaluation of conductive biomaterials. The knee and hip joints belong to the most often implanted joints but they are the most frequently exchanged, too. Therefore, the verification of their quality is necessary before they are inserted into the body as damaged materials may cause some problems.

The purpose of this article was to find the frequency which successfully detects five different defect with various depths and displays differences between them. Results were obtained using numerical simulations from Opera software and they were experimentally verified subsequently.

The most suitable frequency  $f = 100$  kHz was determined based on these measurements. Detections by numerical simulation were successful with all frequencies and their graphs provide opportunity to determine the depth of each defect inside the evaluated material. The experimental measurements representing the reality have demonstrated that these types of defect, it means surface defects can be detected only with higher frequencies. It can be concluded that chosen suitable excitation frequency and type of used probe is very important for non-destructive testing by eddy current method.

Eddy current testing requires a very small distant between the probe and evaluated material, hence this method is possible to use only for applications outside the human body, it means as the final inspection of prostheses before their implantation.

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