Tomasz PRAUZNER

Jan Dlugosz University in Czestochowa, Institute of Technical Education and Safety

doi:10.15199/48.2015.12.53

Finite Element Method in an analysis of selected parameters of an inductive sensor for protective coatings measurements

Abstract: *The paper presents results of simulation experiments on an inductive sensor used in safety engineering for measuring thickness of protective coatings. Selected operation parameters of the sensor were tested by means of the Finite Element Method. The study is part of a research project conducted at the Institute of Technical Education and Safety, Jan Dlugosz University in Częstochowa. The objective of the study is to verity the results obtained in laboratory experiments carried out in the Institute of Telecommunications and Electromagnetic Compatibility, Częstochowa University of Technology.*

Streszczenie: *W artykule przedstawiono wyniki badań symulacyjnych wybranych parametrów pracy czujnika indukcyjnego wykorzystywanego w inżynierii bezpieczeństwa w pomiarach grubości powłok ochronnych za pomocą metody elementów skończonych. Badania symulacyjne MES wykonano w ramach prowadzonego projektu badawczego w Instytucie Edukacji Technicznej i Bezpieczeństwa Akademii im. Jana Długosza w Częstochowie. Celem badań była weryfikacja wcześniejszych wyników badań laboratoryjnych pracy czujnika indukcyjnego wykonanych w Instytucie Telekomunikacji i Kompatybilności Elektromagnetycznej Politechniki Częstochowskiej.* ***(Metoda elementów skończonych w analizie wybranyxch parametrów indukcyjnych czujników grubości powłok)***

Keywords: simulation, modelling, FEM, inductive sensor
Słowa kluczowe: symulacja, modelowanie, MES, czujnik indukcyjny

Introduction

The inductive sensor consists of two windings on a ferromagnetic core (Fig.1,2). One of the windings is powered by a measuring signal of variable frequency and fixed amplitude. The other winding is used for determining the magnitude of the magnetic field generated by eddy currents induced in the material under scrutiny to find the thickness of a metal coating [1,2]. The sample consists of three steel sheets covered by zinc and varnish. Laboratory experiments carried out in the metrology lab at Czestochowa University of Technology were aimed to determine the sensitivity of the sensor with respect to the input frequency and voltage on the power supply winding [3,4,5]. The results were subsequently verified by means of the 3D FEM model at the Institute of Technical Education and Safety, Jan Dlugosz University in Częstochowa [6,7]. The results obtained by means of the FEM are also utilised towards constructing a precise model to be used in further experiments. The results will at the same time serve the purpose of verifying the accuracy of the sensor simulation model and showing a direction for improvements and implementing new solutions. FEM's method is commonly used in simulations using a computer. Simulation is often the only way to obtain calculations which are difficult to perform in the laboratory. It's used to compare the calculations of different testing methods, too [8-14]. The simulation model can also be a tool for assessing the usefulness of simulation programmes employed in the didactic process of a technological university [15].

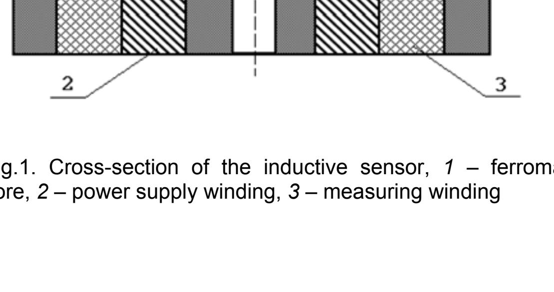

Fig.1. Cross-section of the inductive sensor, *1* – ferromagnetic core, *2* – power supply winding, *3* – measuring winding

Fig.2. Ferrite core applied in the study P22/13, manufactured by FERROXCUBE

Testing the operation parameters

In the laboratory tests, measuring signals of various shapes were used to perform measurements, including sinusoid signals (Fig.3.) and triangular signals (Fig.4.).

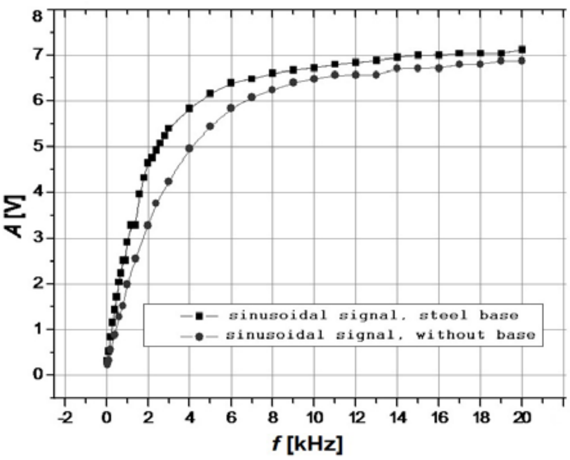

Fig.3. Amplitudes of the measuring sinusoid signal recorded by the inductive sensor on the surface examined and without a surface.

It can be observed on the basis of the measurements that the inductive sensor has the highest sensitivity for the sinusoid signal of the measuring frequency in the range 1 kHz to 6 kHz (for U=1,5-6,5 [V]).

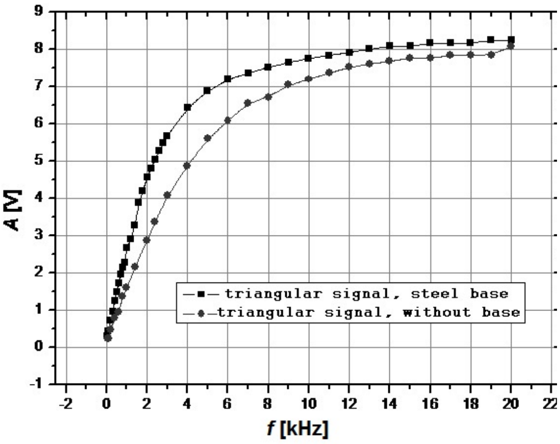

Fig.4. Amplitudes of the measuring triangular signal recorded by the inductive sensor on the surface examined and without a surface

For the triangular signal, the highest sensitivity of the sensor on the surface examined is in the frequency range 1 kHz to 10 kHz (for U=1,5-8 [V]). By comparing the results of the measuring signal amplitudes on the car body steel sample, it can be stated that the curves are of similar shapes. In the range up to 3 kHz the characteristics coincide and differences occur for frequencies above 3 kHz where higher amplitudes can be observed for triangular signals of the same frequency as sinusoid ones. Because of this, it is possible to utilise signals of the same frequency but different shapes in testing the thickness of zinc and varnish coatings on steel substrates. In the laboratory tests, the power supply winding was connected with a function generator and powered with a sinusoid signal of various frequencies and amplitudes. The measuring winding was connected to a measuring card or to a multimeter. Fig. 5 presents selected measurement results for three protective coatings of different thickness on an s substrate of the same thickness.

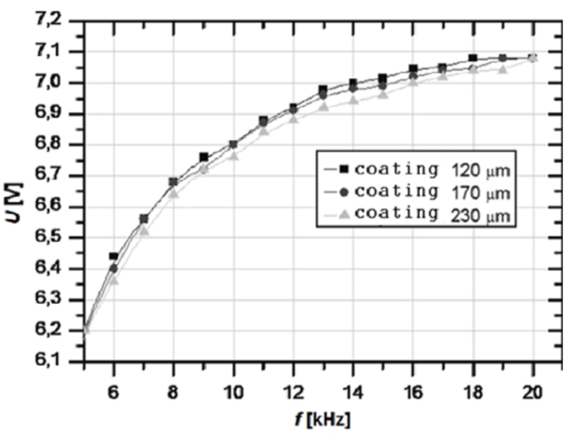

Fig.5. Measurements of the zinc-vamish coating thickness performed by means of a sinusoid signal

On the basis of the results obtained it can be stated that the sinusoid signal displays the highest sensitivity in the frequency range 11 kHz to 18 kHz (for U=6,8-7,1 [V]). For lower and higher frequencies than the range specified the measurements results for the particular layers are weakly distinguishable, since the values of the measuring signal amplitudes are very close. This is associated with the depth of the signal penetrating into the sample under scrutiny.

The sensor design and simulation on the basis of a 3D model

Fig.6 presents a model of the sensor, drawn in the Ansys environment on the basis of the technological parameters and dimensions of the sensor constructed for the laboratory tests [16].

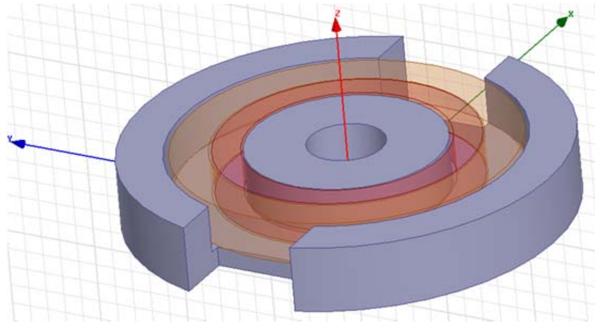

Fig.6. A schematic 3D model of the inductor sensor

The modelling process consisted of a few editing steps. At first, the research problem was formulated and a simulation was enabled in the required environment. Next, electric and magnetic properties of the material were defined, and the shape of the system "sensor – steel sheet samples" was represented. Then, the boundary parameters for the edges, vertices and blocks of the model were determined. Finally, the FEM computations were performed and the results were visualised.

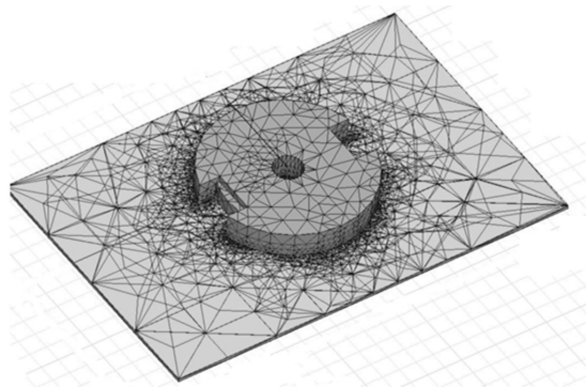

Fig.7. A FEM mesh mapped on the sensor and the sample surface

Since the sensor system was in fact supplied by AC of various characteristics, the programme was set to the computational environment called "eddy current". To this end, a number of electric systems of the power supply winding were modelled (Fig.8). The results of the simulation for the steel sheet samples are presented visually as tonal transition of the induction B and of the magnetic field intensity H (Fig.9,10).

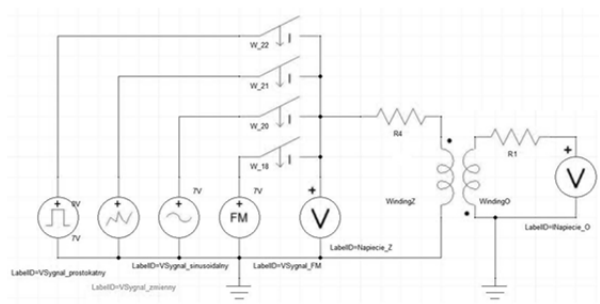

Fig.8. Diagram of the power supply system on the primary winding and the voltage measuring system on the measuring winding.

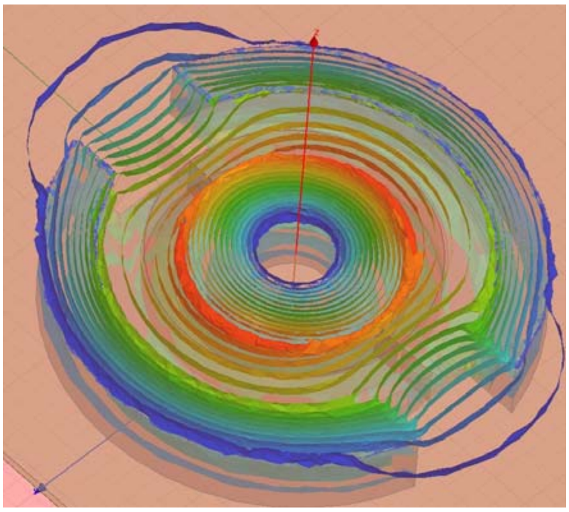

Fig.9. Visualisation of the diverging induction B of the electromagnetic field at the contact of the sensor and the surface of the sample under test (view from the sample's side)

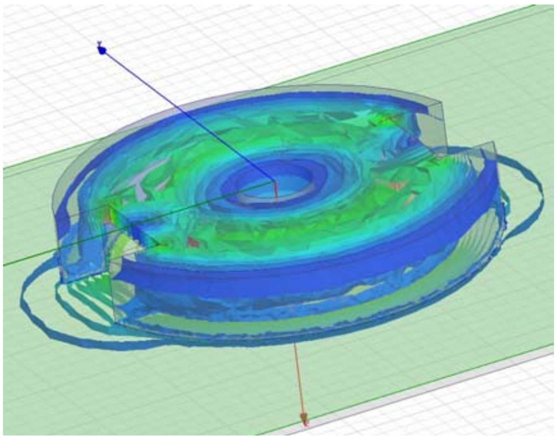

Fig.10. Visualisation of the diverging induction B of the electromagnetic field at the contact of the sensor and the surface of the sample under test (view from the upper side of the sensor)

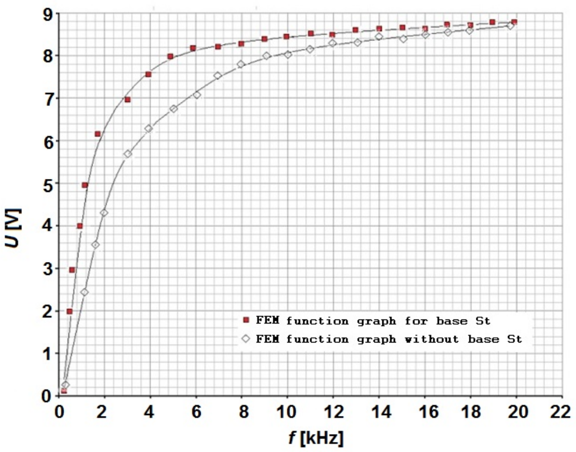

Fig.11. Measuring signal amplitudes obtained from the analysis of the model operation on the surface under test and without a surface for a sawtooth (triangular) signal

Analysis of the results on the basis of the FEM computations

On the basis of the model described above, a sawtooth voltage characteristics was obtained for the measuring winding (Fig.11,12). Then, it was compared to the characteristics obtained in the laboratory experiments. Since the results for the sinusoid signal were satisfactory, further analyses were undertaken in order to determine the sensor's sensitivity for testing the steel sheets with protective coatings. The results obtained indicate that when a sinusoid signal is used, the highest sensitivity holds in the frequency range 0,5 kHz to 19 kHz, both on the sample surface and without a surface, for U=6,8-7,1[V]. For samples with various coating thickness, the highest sensitivity can be obtained in the frequency range 6 kHz to 18 kHz. The results of the laboratory experiments and the FEM computations are presented in Table 1.

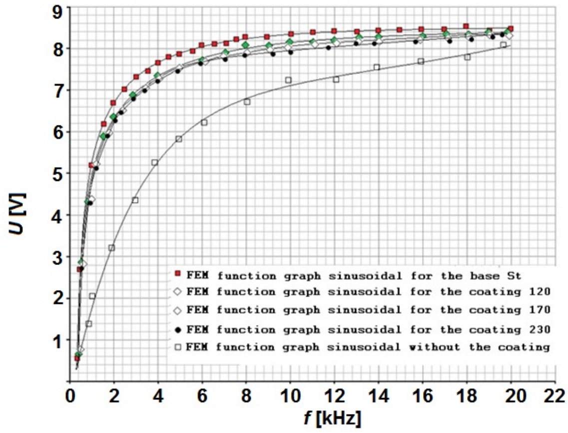

Fig.12. Measuring signal amplitudes obtained from the analysis of the model operation on the surface under test and without a surface for a sinusoid signal

Table 1. Results of the laboratory experiments and of FEM computations.

	Frequency *f* [kHz] range for the highest sensitivity of the sensor *A* [V]			
	Results of lab tests		Results of FEM simulations	
	Triangular signal	Sinusoid signal	Triangular signal	Sinusoid signal
With substrate St	1-10 kHz for U=1,5-8 [V]	1-6 kHz for U=1,5-6,5 [V]	1-10 kHz for U=2-8,4 [V]	0,5-19 kHz for U=6,8-7,1 [V]
Substrate with protective coating 120,170, 230 [μm]	No data	11-18 kHz for U=6,8-7,1 [V]	No data	6-18 kHz For U=7,8-8,3 [V]

Concluding remarks

The objective of the study was to compare and analyse measurement results obtained in laboratory tests by means of traditional measuring instruments with results obtained by applying the FEM. On this basis, the following conclusions can be drawn:

- The results obtained provided evidence that simulation programmes can support measurement results, without however guaranteeing their correctness. The lab results are here treated as real, although they are also burdened with an error, this error is smaller than that of simulations;
- Modelling and simulation have to be preceded by constructing a precise design of the project. The accuracy of output data crucially depends on the accuracy of the model;
- The highest sensitivity of the sensor with a triangular signal determined by means of both methods for the St substrate and without a substrate oscillated around the frequency 1 to 10 kHz;

- Comparing the results obtained by means of the two methods for the sinusoid signal shows a significant discrepancy;
- The results of sensitivity obtained for samples with a protective coating (of all the different thicknesses) are not identical, nevertheless they are within the frequency interval 6 to 18 kHz for the FEM and a smaller interval of 11 to 18 kHz for the laboratory method;
- The results indicate that the sensor maximal sensitivity was obtained for significant observable differences in the measuring signal amplitude;
- It can be hypothesised that the differences between the lab results and the simulation results lie in the construction of the FEM model. Possibly, there are inaccuracies in the 3D design, which can cause imperfections in the sensor construction and in the representation of the sensor-sample contact surface;
- Designing a virtual model can be a subject to a programming error. Additionally, there can be differences between technical specifications and the actual properties of a material, such as a ferromagnetic core;
- The FEM limits an impact of stochastic factors and of external interference, which may influence laboratory measurements;
- FEM modelling makes it possible to develop a model affording a good compromise between computational accuracy and cost of time spent on modelling, computing and analysing the results;
- The results of experiments and their verification by means of the senor model developed with the use of FEM are an attempt to create a virtual environment which can be employed in future research aimed at obtaining innovative designs of the sensor characterised by greater accuracy and reliability;
- The simulation model constructed is an example of implementing modern information technology both in scientific research and in the development of didactic aids useful for educating future specialists in engineering.
-

REFERENCES

[1] Tumański S., Czujniki pola magnetycznego, *Przegląd Elektrotechniczny,* 89 (2013), nr.10,1-11

[2] Prauzner T., Ptak P., Analiza parametrów pracy wybranych czujników pola magnetycznego, *Przegląd Elektrotechniczny*, 90 (2014), nr.12, 273-276

[3] Ptak P., Borowik L., Diagnostyka zabezpieczeń antykorozyjnych na potrzeby elektroenergetyki, *Przegląd Elektrotechniczny*, 88 (2012), nr.9a, 142-145

[4] Ptak P., Prauzner T., Badanie czujników detekcji zagrożeń w systemach alarmowych, *Przegląd Elektrotechniczny*, 89 (2013), nr.10, 274-276

[5] Prauzner T., Effectiveness of magnetic detectors in alarm systems, *Przegląd Elektrotechniczny,* 90 (2014), nr.12, 269-272

[6] Prauzner T., Zakłócenia elektromagnetyczne w elektronicznych systemach alarmowych, *Przegląd Elektrotechniczny,* 88 (2012), nr.12b, 205-208

[7] Bianchi N., *Electrical Machine Analysis Using Finite Elements.* Taylor & Francis Group, (2005)

[8] Bolkowski S., Sikora J., Skoczylas J., Sroka J., Stabrowski M., Wincenciak S., *Komputerowe metody analizy pola elektromagnetycznego,* Wydawnictwa Naukowo–Techniczne, (1993)

[9] Grishkevich A., Piątek Ł., Burmutaew A., Frequency and outage duration in electric power systems. *Przegląd Elektrotechniczny*, 85 (2009), nr.3, 220-222

[10] Jabłoński P., *Metoda elementów brzegowych w analizie pola elektromagnetycznego,* Wydawnictwo Politechniki Częstochowskiej, (2003)

[11] Jakubiec B., Model elektrycznego układu napędowego małego systemu mobilnego, *Przegląd Elektrotechniczny*, 89 (2013), nr.12, 173-176

[12] Jin J.M., *The Finite Element Method in Electromagnetics*, Wiley, IEEE Press, (2002)

[13] Kuczmann M., Iványi A., *The finite element method in magnetics*, Academic Press, Budapest, (2008)

[14] Olesiak K., Application of the fuzzy controller in the speed control system of an induction motor, *Przegląd Elektrotechniczny*, 89 (2013), nr.12, 336-339

[15] Noga H., Metody socjometryczne w edukacji techniczno – informatycznej, *Trendy ve vzdělávání, Informaćni technologie a technické vzdělávání,* (2009), 165-169

[16] Xiaolin Ch., Yijun L., *Finite element modeling and simulation with ANSYS Workbench,* CRC Press, (2014)

***Autor**: dr Tomasz Prauzner, Jan Dlugosz University in Czestochowa, Institute of Technical Education and Safety, Al. Armii Krajowej 13/15 42-200 Częstochowa, phone: 508178818*

E-mail: matompra@poczta.onet.pl