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MULTICRITERIAL OPTIMISATION OF DIAGNOSTIC EQUIPMENT USING CAE SOFTWARE

WIELOKRYTERIALNA OPTYMALIZACJA Z WYKORZYSTANIEM OPROGRAMOWANIA CAE NA PRZYKŁADZIE WYBRANEGO URZĄDZENIA DIAGNOSTYCZNEGO

A b s t r a c t

Development of new diagnostic methods and tools is necessary to ensure the required safety levels in machine operation. Application of Computer-aided Engineering software and FEM modelling approach to the design and prototyping makes the fabrication NDT (Non-Destructive Testing) devices an easier and cheaper task, improving their efficiency and performance. Furthermore, computer methods allow the multi-criteria optimization of diagnostic devices in the context of the specified objective functions.

Keywords: Computer Aided Engineering, FEM method, magnetic head for non-destructive testing of rope, multi-criteria optimization

S t r e s z c z e n i e

Nieustanny rozwój metod i środków diagnostyki technicznej jest niezbędnym krokiem dla zapewnienia odpowiedniego poziomu bezpieczeństwa eksploatacji maszyn, urządzeń i obiektów technicznych. Zastosowanie w prototypowaniu i działaniach projektowych komputerowego wspomagania prac inżynierskich, modelowania MES itp. narzędzi wpływa znacznie na czas i koszty wytwarzania urządzeń dedykowanych dla Nieniszczącej Diagnostyki Technicznej, ale również na skuteczność i efektywność ich działania, a przy tym umożliwia wykonywanie szeroko rozumianej wielokryterialnej optymalizacji urządzeń pod kątem danych funkcji celu.

Słowa kluczowe: Komputerowe wspomaganie prac inżynierskich, metoda elementu skończonego, głowica magnetyczna do badania lin stalowych, wielokryterialna optymalizacja

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1. Introduction

Computer aided engineering is a common feature in designing of various types of machines and installations in the 21st century. The CAE (Computer Aided Engineering) software supported by the designer experience provides an excellent tool allowing the minimization of the prototyping time, the time required for problem solving and minimization of costs associated with project implementation.

The FEM approach is one of the most widespread methods employed in CAE software. Operations involving computer-aided design, engineering, simulations and calculations supported by the FEM methods are also widely used in prototyping and in broadly understood optimization of diagnostic systems. These systems include magnetic sensor heads for wire rope inspection which enable the non-destructive testing of their technical condition, endorsing the decisions to discard or admit ropes for further service. Those sensor heads utilize the constant magnetic field and detection of the magnetic leakage field around the rope defects (i.e. a broken wire). Definition of metrological and functional parameters of the device is a key at the stage of design.

2. Scope of tests

The problem presented in this study is associated with optimization of a sensor head for rope inspection at their attachment points, supported by the CAE – ANSYS software and FEM modelling. The most typical rope attachment is in shape of a tapered section, which is a rope end section unlaid into single wires forming a brush cased with molten metal or resin to form a taper. The performance of such attachments is rather unsatisfactory because the load-carrying rope is subjected to tensile forces of varying magnitude leading to rope oscillations, whilst the taper is typically fixed on a joint such that 5 DOFs are subtracted (leaving only the rotation around the axis of the fixing bolt) (Fig. 1a).

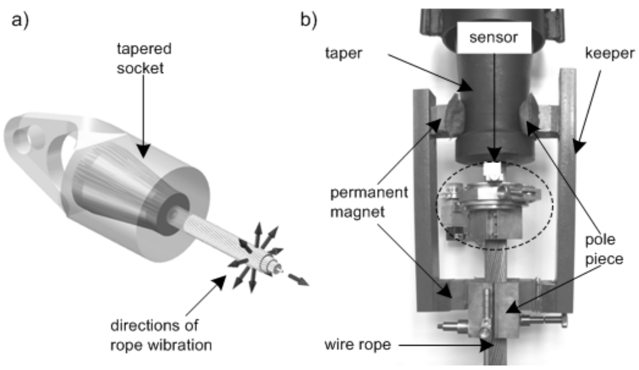


Fig. 1. a) Rope attachment in a socket – model, b) Magnetic sensor head placed on the rope attachment point (tapered section)

Rys. 1. a) Zamocowanie liny w stożku – model, b) Głowica magnetyczna zainstalowana na zamocowaniu (zakończeniu) liny w stożku

The sensor head with a smart transducer is a mechatronic system incorporating the mechanical, electric and electronic parts. To develop a method for assessing the technical condition of wire ropes at their attachment points without the need to dismount the objects to be inspected it was required that the magnetic circuit be manufactured that has technical parameters ensuring the desired metrological features. The magnetic circuit comprises pole pieces placed upon the rope and the tapered section, permanent magnets placed upon pole pieces and magnet keepers closing the magnetic circuit [1] (Fig. 1b).

The measuring sensor utilizes the magnetic induction phenomena or the Hall effect [2]. It performs the rotating motion with respect to the rope axis, corresponding to variations of the radial component of magnetic induction, being the function of local change of the rope's ferromagnetic section. In the light of the measurement procedure which involves the rotating motion of the sensor, it is important that the value of the radial component of magnetic induction should be identical at all points around the rope (on the same radius). The main problem associated with the sensor head design is the asymmetry of the magnetic field distribution inside it, in planes parallel to the rope axis near the tapered section.

3. Multi-criteria optimization

In order to define the metrological and technical parameters of the device, it is required that their effects on the formulated objective functions be duly determined. The multi-criteria optimization procedure uses the following objective functions $fn(x)$ (Fig. 2):

- mass of the whole device should be as small as possible – f_1;
- magnetic leakage field distribution around the rope, near the tapered rope section is of key importance and the relationship between magnetic induction and distance from the plane determined by the tapered section should be roughly linear – $f_2(x)$;
- the value of magnetic induction in the rope (metrological parameter) guaranteeing the detection of rope defects near its centre exceeds 1.4 T – $f_3(x)$

  where:

  x – is the vector of decision variables.

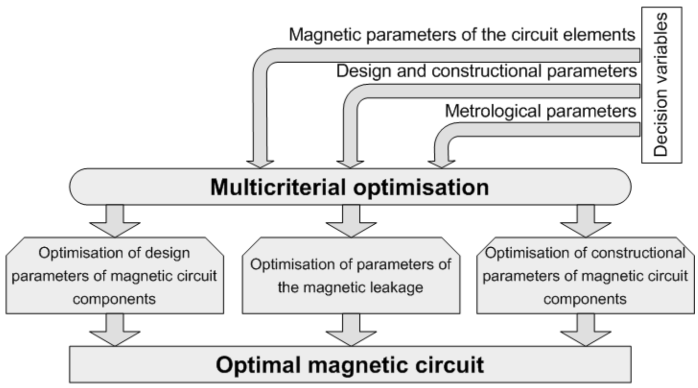


Fig. 2. Multi-criteria optimization of a magnetic circuit

Rys. 2. Problem optymalizacji wielokryterialnej obwodu magnetycznego

Multi-criteria optimization is an attempt to find the vector of decision variables which should satisfy the given requirements and optimize the vector of a function, whose components represent particular objective functions.
The multi-criteria optimization problem can be written as:

$$F(x) = [f_1(x), f_2(x), f_3(x)]$$

We can use this function's vector in terms of various constraints in the form of equalities and inequalities:

$$g_i(x) \leq 0 \quad i = 1, \ldots, n$$

$$h_i(x) = 0 \quad i = 1, \ldots, p$$

In other words, multi-criteria optimization is an attempt to find the vector of decision variables:

$$x = [x_1, x_2, ..., x_k],$$

which should satisfy the following conditions:

$$g_i(x) \leq 0 \ (i = 1... n),$$

$$h_i(x) = 0 \ (i = 1 ... p)$$

and which optimizes the function's vector whose components represent the objective functions: minimization of the mass of the device, magnetic field distribution inside the sensor head and minimization of measurement errors due to asymmetry of this distribution and the required level of magnetic induction in the rope to ensure the good detection capability

$$F(x) = (f_1(x), f_2(x), ..., f_k(x))$$

Decision variables x, being technical and constructional parameters of the device (design variables), are shown in Fig. 3.

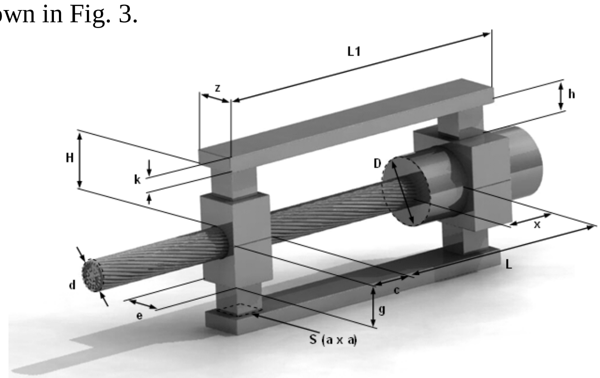


Fig. 3. Decision variables for optimization of the magnetic circuit

Rys. 3. Zmienne decyzyjne optymalizacji obwodu magnetycznego urządzenia

Decision variables include:

– metrological parameters (B1, distribution of magnetic induction in the rope),
– (magnetic) materials parameters of permanent magnets (Hc, Br) and other components of the magnetic circuit: magnetic keepers and pole pieces (relative magnetic permeability μ),
– constructional parameters of the magnetic shaped piece (cross section S, height-h), of the keeper (thickness k, width z, length L1) and of the pole pieces (c, g, e),
– technical parameters of the magnetic circuit: length of the magnetized tapered section x, distance between the keeper and the rope H, the length of magnetized rope section (L-x).

This analysis is limited in scope, so the authors investigate only the effects of selected decision variables on the previously defined objective functions. In accordance with the predetermined assumptions, certain constraints are imposed in the form of equalities and inequalities. Inequalities are associated with metrological parameters, such as the value of magnetic induction in the rope which must be in excess of 1.4 T. Another constraint in form of an inequality is associated with technical parameters, such as: H, (L-x), being the consequence of the need to ensure sufficient room in which the non-magnetic part of the device can be placed. Constraints in the form of equalities are related with the rope diameter, to which a given sensor head is dedicated or parameters of the pole pieces (c, g, e) , associated with d, D and S (Fig. 3).

The first objective function $f_1(x)$ is associated with minimization of masses of permanent magnets [min (S x h) and the mass of the magnetic keeper [min (h x b x L1], at the same time the constraints associated with the induction distribution in the rope and in the keeper will still hold. Implementation of the second objective function $f_2(x)$, associated with the magnetic leakage distribution, depends on the parameters L, X and H defining the mutual relationships (distances) between the components of the magnetic circuit in the sensor head. The third function $f_3(x)$ is associated with the rope diameter d and magnetic and constructional parameters of permanent magnets. In some objective functions the same decision variables will affect the final result of the analysis. Different vectors of decision variables might yield the same optimal solutions in the form of identical objective function vectors, for example parameters L, X, H should also slightly affect the function $f_1(x)$ or its constraint in form of an inequality.

The FEM package requires that the problem be written in the parametric form, such that a variation of certain parameters (design variables) in the optimization algorithm should lead to subsequent variants getting nearer and nearer the optimal solution to thus formulated problem. The significance of the objective functions might be determined by the method of weighted objectives:

$$F(x) = \sum_{i=1}^{k} w_i \cdot f_i(x)$$

where:

k – number of functions,

x – vector of solutions,

w_i – weight factors such that: $w_i \in [0, \ 1]$ and $\sum_{i=1}^{k} w_i = 1$.

Accordingly, multi-criteria optimization is brought down to the single-criteria problem. For the considered system of 3 objective functions, the following weighing factors are assumed: $w_1 = 0.2$; $w_2 = 0.3$; $w_3 = 0.4$.

4. Numerical analysis using FEM modelling

The numerical analysis involved the testing of 13 configurations of decision variables and their impacts on particular objective functions were found accordingly. The FEM calculations [3] were performed for a 3D model, in order to check the leakage filed distribution along the rope and in planes normal to its axis, in the operative range of the sensor. The boundary conditions are defined (1 – applied excitation- magnetization curve; 2 – surrounding air) and specific physical parameters of the magnetic materials are ascribed to individual components of the magnetic circuit.

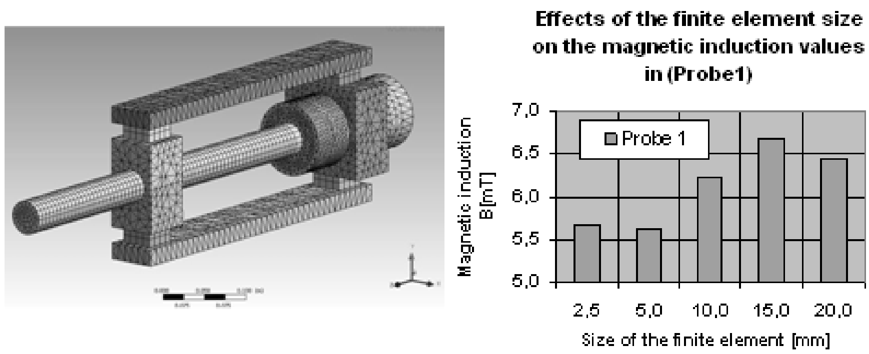


Fig. 4. Discrete model and the influence of the finite element size on measurement data at the given measurement point

Rys. 4. Model dyskretny i wpływ wielkości elementu skończonego na wyniki pomiaru w wybranym punkcie pomiarowym

In further stages the analyzed space is discredited. The effects of the finite element size have a major importance on the magnetic induction values (Fig. 4).

Finally, 128 points are determined for each of the analyzed options, yielding 640 numerical values revealing the magnetic leakage filed distribution within the space in which the sensor operates.

To realise the first objective function, the authors checked how fluctuations of particular decision variables should affect the mass of the sensor head in the magnetic circuit for the analysed variants. The masses were evaluated based on the volume of the given element and density of the material ascribed to that element. For materials St1 and St3 we assume $\rho = 7859$ kg/m^3, and for the shaped pieces NdFeB $\rho = 7000$ kg/m^3 (Fig. 5).

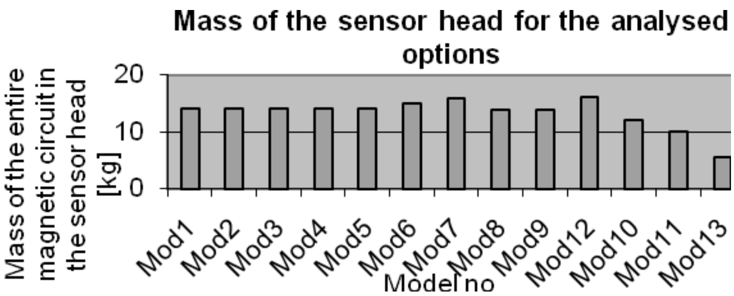
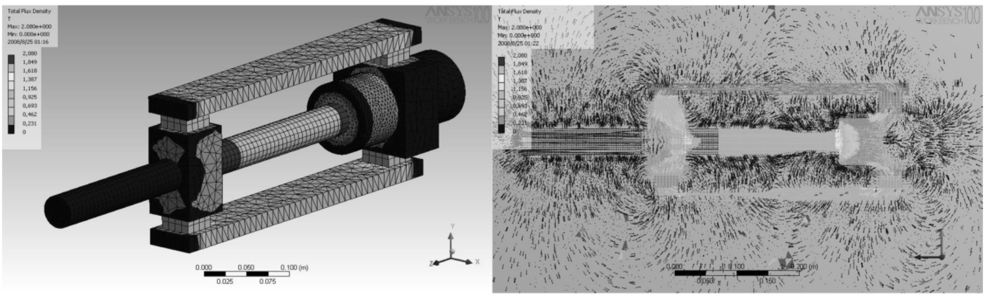


Fig. 5. Mass of the device for particular options of decision variables

Rys. 5. Masa urządzenia dla poszczególnych wariantów zmiennych decyzyjnych

To realize the second objective functions aimed at the optimal magnetic field distribution in the magnetic circuit and the surrounding space, the authors sought to identify the tendencies in magnetic induction fluctuations and their causes, instead of measuring its actual values. The key factors involved in fluctuations of magnetic induction include:
– type of changes (linear or nonlinear),
– magnitude of fluctuations,
– increasing or decreasing tendency.



Rys. 6. Graficzne wyniki analizy MES (konturowe, wektorowe)

Fig. 6. Graphic results of the FEM analysis (3 D contours, 2 D vectors)

Thus obtained 8000 analytical data (numerical values) and graphic results (Fig. 6), including contours, vector plots, iso-surfaces and contour lines yield the plots showing magnetic field distribution along the rope and in planes normal to it (i.e. the planes of the sensor's motion) (Fig. 7). The inferring procedure is then applied to find out how a variation of decision variables in optimization, in particular of the parameters x, L, H, should affect the field distribution inside the device.

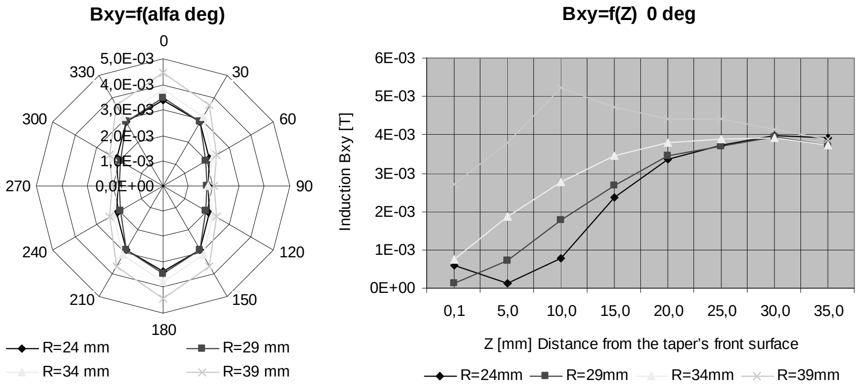


Fig. 7. Radial component of magnetic induction (measured by the sensor) in the plane parallel to rope axis and in the function of distance from the taper's front surface

Rys. 7. Wartości składowej promieniowej indukcji magnetycznej (wielkość mierzona przez czujnik) w płaszczyźnie prostopadłej do osi liny wokół niej oraz w funkcji odległości od powierzchni czołowej stożka

As regards the third objective function, the authors analyzed how fluctuations of decision variables should affect the induction level in the rope- a metrological parameter (fig. 8). Magnetic induction in the rope is associated both with material properties of particular circuit components and permanent magnets and with the circuit geometry and interactions between sensor head elements.

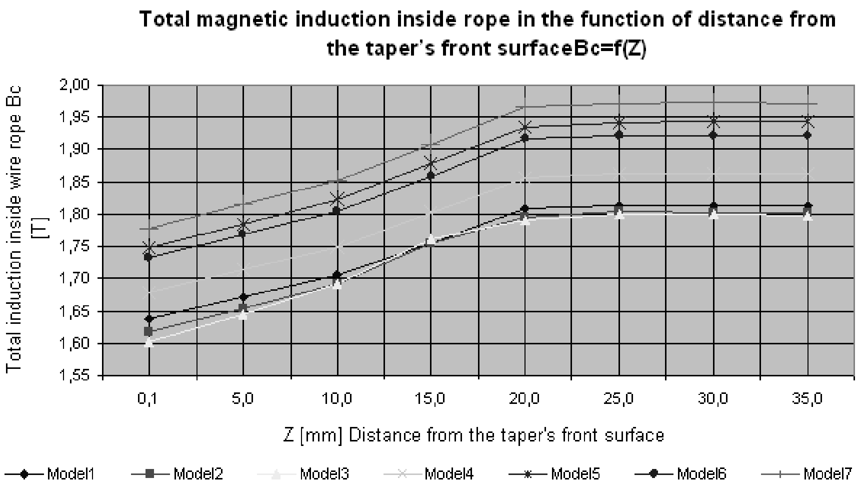


Fig. 8. Magnetic induction in the rope in all considered variants of the analysis

Rys. 8. Wartość indukcji magnetycznej w linie dla poszczególnych wariantów analiz

5. Conclusions

Metrological parameters of a sensor head for inspecting rope attachment points are investigated. Three objective functions are defined for the purpose of multi-criteria optimization of the magnetic circuit structure. It is shown how variations of geometric parameters of the magnetic circuit in the sensor head (decision variables) should affect each of the considered objective functions and the nature of the magnetic field distribution around the rope. Computer-aided engineering software is shown to be a useful tool for engineers, supporting the design and fabrication of diagnostic devices.

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