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FEM modelling of magnetostrictive composite materials

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ABSTRACT

Purpose: The paper presents a numerical model for the analysis of magnetostriction in composite materials in polymer matrix reinforced by $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles. The properties were determined by taking into account the applied stresses and magnetic field intensity.

Design/methodology/approach: The finite element method for simulation the magnetostriction phenomenon was established by theoretical analysis based on experimental results.

Findings: Thanks to the finite element method the numerical model has been formulated, enabling to simulate behavior of dynamically exciting rod with the nonlinear constituted model of magnetostrictive effect. The results received from experiments and simulations confirmed accuracy of this model for operating conditions, enabling a selection of magnetostrictive composite material with polymer matrix reinforced with $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles for specific application.

Research limitations/implications: It was confirmed that using the finite element method can be a way for reducing the investigation cost. This paper proposes analysis which is efficient with respect to the number of simplifications in numerical model and accuracy of results.

Practical implications: The proposed method could be helpful in the design process of magnetostrictive composite materials.

Originality/value: Modelling based on the finite element method allows to simulating behavior of dynamically exciting rod with the nonlinear constituted model of magnetostriction phenomenon.

Keywords: Numerical techniques; Finite Element Method; Terfenol-D; Composites; Magnetostrictive materials

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

Magnetostrictive materials' ability to generate deformations in wide frequency range - until now unavailable in piezoelectric materials - allows them to compete effectively with traditional transducers [1-2]. The magnetostrictive phenomenon is a source of many applications in modern technology, and thanks to the possibility of changing resilient deformation energy to magnetic one, magnetostrictive materials are used in sensors and actuators of vibrations and dislocations. One of the main applications of those materials are sensors assembly - example of it can be the vibration sensor made of magnetostrictive materials in a form of rods surrounded by measuring coils. Principle of its operation uses stresses made under influence vibration in the material, which produce magnetic field and generates changeable electric voltage in the measuring coils [3-4].

Magnetostrictive transducers are used in high-class industrial devices, motorization, biomedical applications and arm industry, among which following can be ranked [5-9]:

- active control of vibration;
- micro-positioning;
- devices used to degas while vulcanization of rubber;
- intelligent plane wings able to change shape depending on flight speed and saving fuel thanks to that;
- generating ultrasound in applications for surgical tools or acoustic devices.

The rising interest in magnetostrictive materials makes it necessary to make an attempt to optimize composition of those materials and production technology. Magnetostrictive composite materials, thanks to its advantages are presenting an attractive alternative for its monolithic equivalents, whilst increasing a range of applications and economical requirements make modelling of magnetomechanical materials more and more attractive [10-14]. In order to design, manufacture and exploit systems made of magnetostrictive composite materials properly it is essential to use not only experimental techniques, but also methods of computer modelling and simulation [5,7].

Herbst at al. [15] conducted a research on composite materials made by hot pressing of $SmFe_2$/Fe and $SmFe_2$/Al and presented approximate model describing its effective magnetostriction. Nan at al. [16] described magnetostriction with the Green function method and Chen at al. [13] measured dependence of magnetostriction in the composite materials with copper, iron, aluminum or glass matrix and – basing on that – it was elaborated a model. However this model is correct only when the Young's modulus of the composite matrix is close to the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ modulus; moreover it is inapplicable for composite materials with the polymer matrix, what is suggested by Guo's at al. research [12,17].

Prediction of composite materials properties, especially controlling it, is a complex issue. Compliance level of results received from theoretical predictions with data obtained experimentally depends on complexity level of physical model of composite material and connected with it mathematical description and the composite manufacturing accuracy level [18-20,34]. In the case of composite magnetostrictive materials, the actuator's designer should take into consideration the relationships between the mechanical characteristics (strain, stress), and magnetic one (i. e. magnetization and magnetic field intensity) (Fig. 1). In addition, magnetostrictive responses for these materials are essentially nonlinear, hysteretic and frequency-dependent [21,22] and - by this fact - it is difficult to develop theoretical model.

Among the numerical methods the most popular one is the finite element method (FEM) [23-29], especially thanks to it commercial packets accessibility, and precision.

The aim of this work is to elaborate simulation of deformations in magnetostrictive materials induced by the magnetic field with variable amplitude and frequency and diverse value of the compressive pre-stress by the finite element model.

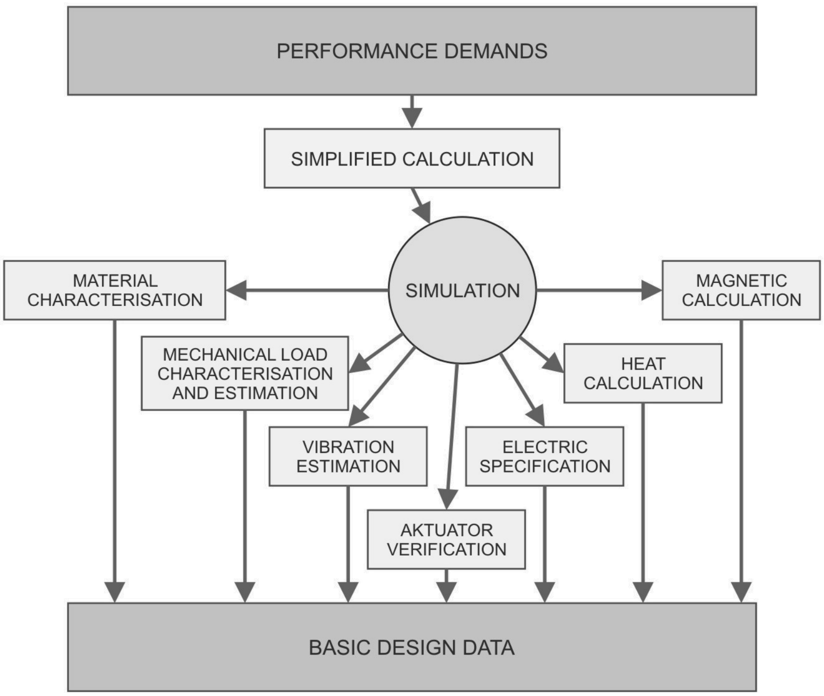

Fig. 1. The design activities regarding a magnetostrictive actuator [7]

2. Identification of magnetostrictive composite materials model parameters

The experimental data obtained for magnetostrictive composite materials [32,33] was used as the basis for determining properties of these materials. It was assumed that building of model for magnetostrictive material system (Fig. 2) has a fundamental importance and according to [7,25,30] it was establish a one-dimensional and nonlinear model for parameters describing physical features reasons, especially magnetic field intensity and compressive pre-stress value.

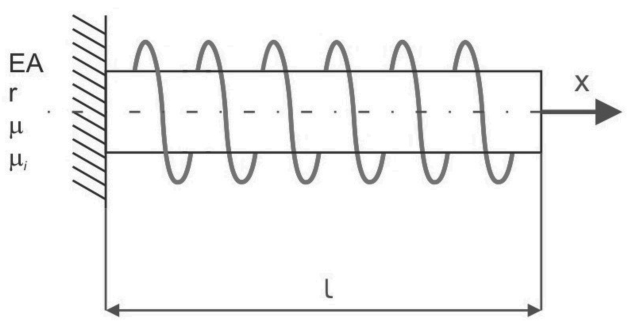

Fig. 2. Magnetostrictive composite rod with coil

It is worth to emphasize that magnetostrictive composite material characterization, as well as identification its model is not easy: its distortion follows under the influence of magnetic field with alternating intensity. In addition the magnetic field would dissipate because of non-magnetic matrix being a binder for magnetostrictive $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles [14-16, 21].

In order to determine the initial-boundary value problem of the magnetostrictive rod forced vibration, the following assumptions were made:

- standard square constitutive model of the magnetostrictive material;
- time-varying magnetic field;
- possibility of applying the compressive pre-stress;
- dependence of composite materials properties from their composition (i.e. volume fraction and size of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles).

2.1. Constitutive relations

For composite materials – according to [6,21] this problem can be solved by means of the general model for the magnetostrictive materials and among them the standard square model (SS) is the most simple. The SS relations means that strain is quadratic with respect to magnetic field [12]. Constitutive relations are basing upon reducing expansion of the Gibbs free energy equation written as:

$$\begin{cases} \varepsilon_{ij} = S_{ijkl}\sigma_{kl} + m_{ijkl}H_kH_l + r_{ijklmn}\sigma_{kl}H_mH_n \\ B_k = \mu_{kl}H_l + m_{klmn}\sigma_{mn}H_l + r_{klmnpq}\sigma_{mn}\sigma_{pq}H_l \end{cases} \tag{1}$$

where:
ε_{ij} – the strain tensor;
S_{ijkl} – the susceptibility tensor;
σ_{kl} – the stress tensors;
m_{ijkl} – the tensor of magnetostrictive modulus;
H_k – the magnetic field vector;
B_k – the magnetic flux vector;
μ_{kl} – the magnetic permeability tensor;
r_{ijklmn} – the tensor of of magnetoelastic modulus.
with r and m determined experimentally in accordance with procedure given in [21]. For one-dimensional case, equation (1) adopts form:

$$\begin{cases} \varepsilon = (\frac{1}{E} + rH^2)\sigma + mH^2 \\ B = (\mu + m\sigma + r\sigma^2)H \end{cases} \tag{2}$$

where E is the Young's modulus, H – the magnetic field and B – the magnetic flux.

There was considered a rod, which can be treated as one-dimensional (1D) model [25,31]. The rod was put under the influence of the magnetic field by winding around them a solenoid coil which was exciting by the alternating current. Moreover, there is taking into account a possibility of application of the compressive pre-stress.

The magnetic field intensity is defined according to the Ampere's law by:

$$H = \frac{n}{l}i(t) \tag{3}$$

where:
n – the number of turns in the exciting coil;
l – the length of the investigated rod;
i(t) – the current inside the coil.

It was assumed that the magnetic field in the rod is homogenous. State of the bias stress describes the following displacement field:

$$u_{o(x)} = \frac{\sigma_o x}{E} \tag{4}$$

where:
σ_o – the compressive bias pre-stress;
x – the x-coordinate.

2.2. Equations of motion

Equations of motion which describes the deformation process under influence of the magnetic field variation was obtained by using the Hamilton's principle. Then theHamilton's functional has a form:

$$I = \int_{t_1}^{t_2} (E_C + U_M - U_E)dt \tag{5}$$

where the kinetic energy E_C of the rod is:

$$E_C = \frac{A}{2}\int_0^l \rho(\frac{\partial u}{\partial t})^2 dx \tag{6}$$

where:
A – the cross-section area of transverse section of the rod;
ρ – the mass density of the rod;
U_M – the magnetic energy of the rod, which is given by:

$$U_M = \frac{A}{2}\int_0^l BHdx \tag{7}$$

The strain energy U_E is expressed by:

$$U_E = \frac{A}{2}\int_0^l \sigma\varepsilon dx \tag{8}$$

By taking into account the constitutive relations (2) in given above equations, there is the following form of the Hamilton's function:

$$I(u) = \int_{t_1}^{t_2}\left[\frac{A}{2}\int_0^l\left(\delta\left(\frac{\partial u}{\partial t}\right)^2 - \frac{E}{(1+E_rH^2)^2}\left(\frac{\partial u}{\partial x} - mH^2\right)^2 + \mu H^2\right)dx\right]dt \tag{9}$$

According to (3), the magnetic field intensity (H) is a given function of time, hence the Hamiltonian operator (9) is a functional of the magneto-elastic displacement of the rod u(x,t) reason. This variational formulation was a base for applying the finite element method to solve the initial-boundary value problem of the magnetostrictive rod forced vibration.

2.3. Finite element model

The rod was dividing onto two-bend finite elements (Fig. 3). The displacement field is given by the linear combination of the shape function:

$$u = N_1u_1 + N_2u_2 = [N_1N_2]\begin{Bmatrix}u_1\\u_2\end{Bmatrix} = Na^{(e)} \tag{10}$$

where N and $a^{(e)}$ represent the shape function matrix, and the nodal displacement bending vector, respectively.

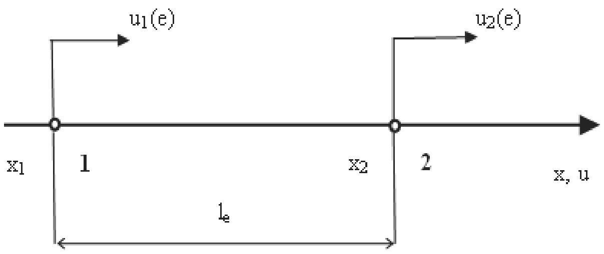

Fig. 3. Finite element scheme

Strains vector can be expressed by the derivatives of the shape function:

$$\varepsilon = \begin{Bmatrix}\frac{du}{dx}\end{Bmatrix} = \begin{bmatrix}\frac{dN_1}{dx}, \frac{dN_2}{dx}\end{bmatrix}\begin{Bmatrix}u_1\\u_2\end{Bmatrix} = Ba^{(e)} \tag{11}$$\

where the differential operator matrix is given by:

$$B = \begin{bmatrix}\frac{dN_1}{dx} & \frac{dN_2}{dx}\end{bmatrix} \tag{12}$$

For the linear shape function according to [8]:

$$N = \begin{bmatrix}\frac{x_2 - x}{l_e}, \frac{x - x_1}{l_e}\end{bmatrix} \tag{13}$$

$$B = \begin{bmatrix}-\frac{1}{l_e}, \frac{1}{l_e}\end{bmatrix} \tag{14}$$

By introducing above approximation into functional (9) it could be – from its stationary condition δI[u] – obtain equation of motion for the finite element:

$$M_e\ddot{u}_e + \frac{1}{(1+E_rH^2)^2}K_eu_e = Q_e \tag{15}$$

where the consistent mass matrix of inertia is written as:

$$M_e = \rho Al_e\begin{bmatrix}\frac{1}{3} & \frac{1}{6}\\ \frac{1}{6} & \frac{1}{3}\end{bmatrix} \tag{16}$$

Stiffness matrix:

$$K_e = \frac{EA}{l_e}\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix} \tag{17}$$

The vector of equivalent nodal forces is equal to:

$$Q_e = \frac{EAmH^2}{(1+E_rH^2)^2}\begin{bmatrix}-1\\1\end{bmatrix} \tag{18}$$

After finite element assembly there is obtained a global equation for entire system:

$$M\ddot{u} + \frac{1}{(1+E_rH^2)^2}KU = Q \tag{19}$$

and boundary conditions for the magnetostrictive rod has adopt form:

$$\begin{cases} \underset{t \geq 0}{\forall} u(0,t) = 0 \\ \underset{t \geq 0}{\forall} \frac{\partial u}{\partial x}(l,t) = mH^2 \end{cases} \quad (20)$$

and after the assembly algorithm, the global Q gives the Neumann's condition in a natural form. It could be notice that equation of motion (19) describes a linear parametric vibration due to the time dependent stiffness matrix. The time dependent factor came from the time-varying magnetic field produced by the exciting coil.

The discrete equation of motion (19) could be integrate by the central difference method or the Newmark's method for example [26]. The initial condition takes form:

$$\underset{x \in (0,l)}{\forall} u(x,0) = 0 \quad (21)$$

or – in the case of applying the compressive pre-stress:

$$\underset{x \in (0,l)}{\forall} u(x,0) = U_0(x) \quad (22)$$

2.4. Data for numerical model

For the numerical model it was assumed the following data: the length of the rod l = 0.25 m, the cross section area $A = 3.14 \cdot 10^{-4}$ m^2, the number of turns in the exciting coil n=120, the alternating current inside the coil $i(t)=i_{max}\sin\omega t$, $i_{max}=10$ A, the circular velocity ω=4.4 kHz, as well as material's data: the Young's modulus E=26.5 GPa, the mass density ρ=9250 kg/m^3, $m=0.09 \cdot 10^{-12}$ m^2/A^2, the magnetic permeability $\mu=9.2 \cdot 4\pi \cdot 10^{-7}$ H/m, $r=-2.77 \cdot 10^{-20}$ $m^2/(A^2Pa)$, and

$$r = \left(\frac{1}{\overline{\overline{E}}} - \frac{1}{E}\right)\frac{1}{H^2} \quad (23)$$

with utilization of substitute-compression modulus.

The time step was determine as $\Delta t = \frac{2\pi}{M\omega}$, where M ≥ 40. The number of finite elements is equal to 20, and data for composite materials was admitted on the base of experimental results [32,33].

3. Description of achieved results of own researches

Data essential for drawing graphs of relation between the magnetic field intensity and the deformation in the direction parallel to the sample axis for a newly developed composite materials were obtained thanks to the numerical analysis and program elaborated for its needs (Fig. 4).

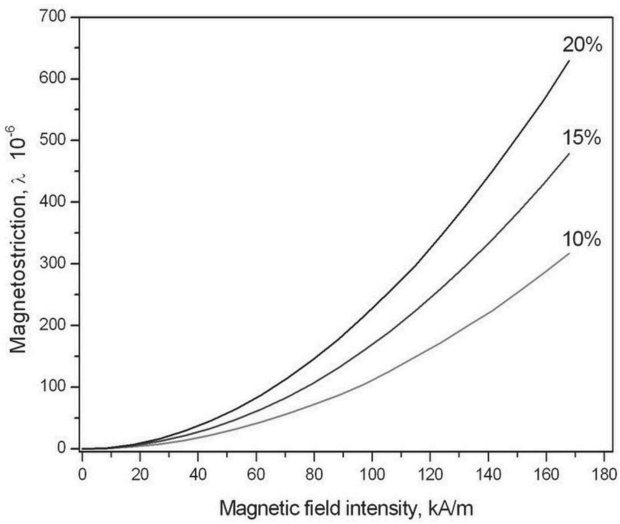

Fig. 4. Relation between the magnetic field intensity and the deformation in the direction parallel to the sample axis obtained as a result of the numerical simulation

Analogical dependence by an application of the compressive pre-stress of the values of 0.1, 0.2 or 0.3 MPa and the displacement amplitude (the current frequency was equal to 50 Hz) is presented in the Fig. 5. The initial flat section (up to 50 kA/m) illustrates that in this range – according to the model – deformations resulting from the magnetostrictive phenomenon do not have considerably influence on sample deformation in longitudinal direction. Moreover – basing on this dependence – it is possible to state that the deformation effected by the compressive pre-stress is much bigger than the deformation caused by the variable magnetic field intensity.

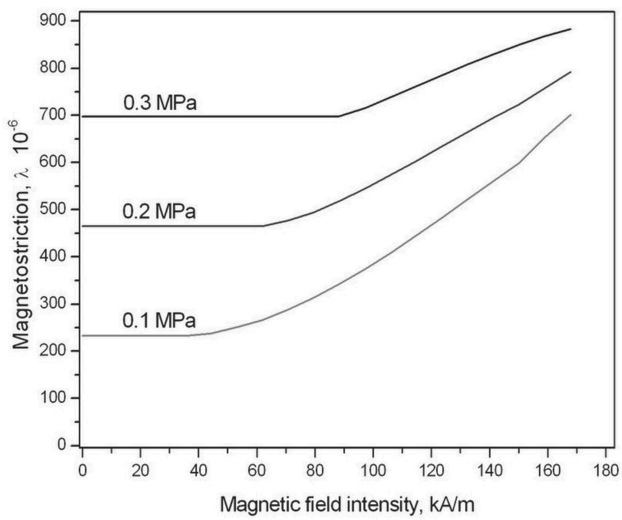

Fig. 5. Relation between the magnetic field intensity and the deformation in the direction parallel to the sample axis with the application of the compressive pre-stress obtained as a result of the numerical simulation

On the presented graphs the magnetostrictive curves do not reach the saturation because the standard square model is used for the simulation. The consideration of this effect would require taking into account different constitutive relations, and then the model would be fully nonlinear and the finite element algorithm would require the iteration procedure. This could cause problems with the convergence of the algorithm and in addition the stability problem may occur.

Increasing the volume fraction of the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder (from 10 to 20%) in the composite material causes growth of the resultant magnetostriction (Table 1), what is in good agreement with experimental results [33]. In addition, the growth of the magnetic field intensity causes the bias of the magnetostriction effect, so maximum values of the magnetostriction are achieved for the magnetic field intensity equals 168 kA/m. The highest magnetostriction was obtained for composite material with the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ volume fraction equals 20%, i.e. $629 \cdot 10^{-6}$. This value is enhanced by the compressive pre-stress, so maximum magnetostriction for all considering cases occurs at the pre-stress level of 0.3 MPa and equals about $883 \cdot 10^{-6}$ (for H=168 kA/m) (Table 2).

A series of numerical experiments based on changing the current frequency values and the rod displacement amplitude reading allowed receiving the amplitude – frequency characteristics, which exemplary course is presented in the Fig. 6. This characteristics has been recorded by the operating current intensity in the coil equal to 100 A. Despite apparatus limitation, which made impossible to measure the magnetostriction as the frequency function, the simulation made by the finite element method is enable to state, that the highest magnetostriction values (i.e. $266 \cdot 10^{-6}$) will be gained at the current frequency equal to about 200 Hz.

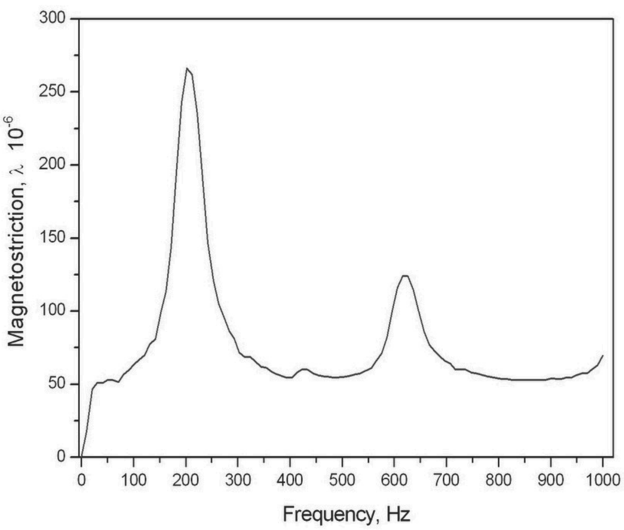

Fig. 6. The amplitude-frequency characterizatic for composite material with polyurethane matrix reinforced with $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles and volume fraction of 20% by operating current intensity in coil equal to 100 A, obtained as a result of simulation

Table 1.
Maximum magnetostriction values for the composite materials reinforced with $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powders

Volume fraction of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$, %	H, kA/m	$\lambda \cdot 10^{-6}$
10%	168	317
15%	168	478
20%	168	629

Table 2.
Maximum magnetostriction values for the composite materials with 20% volume fraction of reinforcing $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powders after application of compressive pre-stress

Pre-stress value, MPa	H, kA/m	$\lambda \cdot 10^{-6}$
0.1	168	701
0.2	168	792
0.3	168	883

4. Conclusions

Thanks to the finite element method the numerical model has been formulated, enabling to simulate behavior of dynamically exciting rod with constituted nonlinear model of the magnetostrictive effect. The proposed model enables to predict the magnetostriction for different applied magnetic field values under and various compressive pre-stress levels. It was found that the magnetostriction values of the composite materials change proportionally to changes of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ volume concentration in the matrix. Maximum magnetostriction equals to $629 \cdot 10^{-6}$ is obtained for the composite material with $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ volume fraction of 20%.

The results received from experiments and simulations confirmed accuracy of this model for operating conditions, enabling a selection of magnetostrictive composite material with polyurethane matrix reinforced with $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles for specific application. By this way the range of performing the expensive optimization of the manufacturing technology and the identification of the magneto-mechanical characteristics in the experimental research is reduced.

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