Sensors & Transducers, Vol. 160, Issue 12, December 2013, pp. 93-98

Sensors & Transducers

© 2013 by IFSA

http://www.sensorsportal.com

The Effect of the External Magnetic Field on the Initial Impulse Attribute for Magnetostrictive Sensors

[1, 3] LONG Shengrong, [2] SONG Xiaochun, [2] ZHONG Yuning,
[1] NIU Ying
[1] School of Mechanical and Electrical Engineering, Nanchang University,
Nanchang Jiangxi 330031, China
[2] Hubei University of Technology, Wuhan Hubei 430068, China
[3] Key Laboratory of Nondestructive Testing (Nanchang Hangkong University),
Ministry of Education, Nan Chang Jiang Xi, 330063, China
[1] Tel: +86 13767140846
E-mail: lornalong@126.com

Received: 9 October 2013 /Accepted: 22 November 2013 /Published: 30 December 2013

Abstract: Magnetostrictive sensors (MsSs) using the magnetostriction effect have many advantages for nondestructive inspections, such as without any contact, movable and easily installed. While the shortcoming of MsSs, for example low SNR and the output affected by the nonlinear magneto-mechanical coupling performance under magnetic field, can limit the use of it. In order to solve this problem, the mechanical dynamics model to excite guided-wave was established which was based on the nonlinear coupled magnetostrictive theory of ferromagnetic material and the generator model of magnetostrictive guided-wave. Using the finite element method (FEM) and numerical simulation, the effect of the bias magnetic field, exciting frequency and exciting current on the particle amplitude were analyzed. The results indicate that the low frequency, heavy current and suitable bias magnetic field can improve the conversion efficiency of magneto-mechanical coupling performance under the condition of considering dispersion. The suitable bias magnetic field is determined by the maximum tangent slope of the amplitude curve. *Copyright © 2013 IFSA.*

Keywords: Dynamical Model, FEM, Magnetostrictive, Ferromagnetic Material, Guided Wave.

1. Introduction

MsSs are types of guided wave sensor considered useful for the structural health monitoring (SHM) of systems. The main advantages over other guided wave sensors, such as piezoelectric sensors, are that no coupling is required, which can be operated on a gap to the material under test and it has a good sensitivity in frequencies up to a few hundred kHz [1]. However the low SNR and output affected by the nonlinear magneto-mechanical coupling performance under magnetic field can limit the use of it. In order to solve these problems, setting up the dynamics model to analyze the effect of parameters on the model is useful.

Guided waves are generated based on the magnetostrictive effect (Joule effect), namely when the ferromagnetic material is magnetized by the external field. Its geometry would change, which is called magnetostrictive effect. For complexity of magnetostrictive effect, such as nonlinear and hysteresis effect, the understanding of characteristics for the magnetostrictive is not deep. The study of MsSs is based on the magnetostrictive from the past literatures. It is often regard the nonlinear constitutive as linear [2, 3]. In fact, the linear model can only apply to the bias magnet around the fixed bias magnetic field. The works of Thompson [2], Il'in and Kharitonov [3], and Wilbrand [4, 5] have defined analytical models for magnetostriction, in terms of elastic and electromagnetic constitutive equations linked by coupling terms accounting for the magneto-mechanical transduction, in analogy with piezoelectric equations which is still the linear model. Gurevich [6] has proposed the method of using electromagnetic acoustic transducer to excite acoustic in the ferromagnetic material and using Green function method to calculate the parameters, V.D. Boltachev [7] studied the theoretical model between electromagnetic and elastic wave in ferromagnetic steel tube. The model considered magneto-elastic coupling, but did not provide effective mathematical calculation and the results are not verified. Finite element magnetostrictive models have been developed in the field of actuators and smart structures to simulate the operation of giant magnetostrictive materials like Terfenol-D [8]. There have been many finite element models for Lorentz force EMATs, but few include magnetostriction.

Research in [15] by M. J. Sablik included electromagnetic theory derived from Maxwell equation, the elastic wave equation in pipe, the boundary condition for solving the electromagnetic wave equation and the relationship between the magnetostriction and magnetostrictive coefficient of coupling is discussed. M.S. Choi [12, 13] established the circuit model for detection system by circuit theory. While these studies basing on the electromagnetic system, the characters of material are not considering. Kwun [9] study the effect of pipe thickness on the reflection wave and Xu [10] pay attention on the bias magnetic field for generating guided waves only by experiments.

In this paper, we pay more attention on the mechanical dynamics model while considering the properties of materials by which the initial impulse of guided wave is got. The FEM model is derived from the Galerkin FEM method by supposing the uniformity of the external magnetic field and no skin effect and proximity effect between conductors in coil. The objective in the present research is to investigate the effect of the external magnetic field, exciting frequency and exciting current on the initial impulse for the longitudinal waves in the pipe by the transmitter of MsSs guided-wave, just shown in Fig. 1.

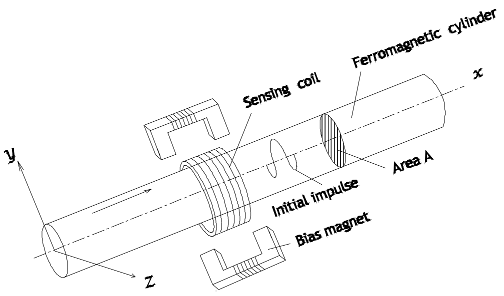

Fig. 1. The initial impulse driving from the transmitter of MsSs in a long ferromagnetic cylinder.

2. Mechanical Subsystem Model of MsSs

In order to determine the initial-boundary value problem of the mechanical model for the MsSs, the following assumptions are made:

1) A nonlinear constitutive model of the magnetostrictive material;

2) time-varying magnetic field.

2.1. Constitutive Relations

According to the experimental results, the behavior of magnetostrictive materials is nonlinear [17], show in Fig. 2.

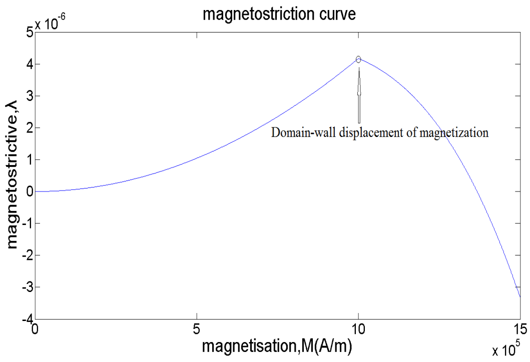

Fig. 2. Magnetostrictive curve of ferromagnetic material.

In this paper, constitutive relations are based on reducing expansion of the Gibbs free energy equation [16] written as:

$$\begin{cases} \varepsilon = \dfrac{\sigma}{E_0} + \left(1 - \dfrac{\sigma}{\sigma_S}\right) \dfrac{\lambda_S}{M^2{}_{WS}} M^2 \\ \quad - \dfrac{\theta\lambda_S \left(M^4 - M^4{}_{WS}\left(1 - \sigma/\sigma_S\right)^4\right)}{M^4{}_{WS}} \qquad , \\ H = \dfrac{1}{k} f^{-1}\left(\dfrac{M}{M_S}\right) - \dfrac{\lambda_S \sigma\left(2 - \sigma/\sigma_s\right)}{\mu_0 M^2{}_s} M \\ + \dfrac{4\theta\lambda_s \sigma\left(M^3 - \sigma_S M^3{}_{WS}\left(1 - \sigma/\sigma_S\right)^3\right)}{\mu_0 M^4{}_{WS}} \end{cases} \tag{1}$$

where the expression of f(x) is as follow:

$$f(x) = \coth(x) - \frac{1}{x}, \tag{2}$$

where σ is the axial pressure; ε-the strain tensor; *H*- the magnetic field; *B* is the magnetic flux; μ_0 -the vacuum permeability; E_0 is the magnetostrictive modulus; χ_0 is the magnetic susceptibility in the initial linear region; M_s is the saturation magnetization; λ_s is the maximum strain; M_{ws} is the domain-wall displacement of magnetization; M is the magnetization; k is the relaxation factor.

The experimental data obtained for magnetostrictive composite materials [16] is used as the basis for determining properties of these materials. It is assumed that building of model for magnetostrictive material system (Fig. 2) has a fundamental importance and a one-dimensional and nonlinear model for parameters describing physical features reasons is established, especially magnetic field intensity.

2.2. Dynamics Model for Longitudinal Guided-Wave Generation

The transmitter of MsSs is assumed as a mass-spring-damping model. So, the dimensions' change of pipe can be regarded as one-dimensional vibration system. The structural dynamic equations of the vibration modal are set up by D′Alembert′s principle, which satisfies the one-dimensional wave equation. A piece of pipe surrounding by the transmitting coil is chosen to analyze the force condition, shown in Fig. 1. So the longitudinal extension is given by Eq (3) while the strain can be written as Eq. (4)

$$\delta = u(x+dx,t) - u(x,t) = u(x,t) + \\ + (\partial u(x,t)/\partial x)dx - u(x,t) = \frac{\partial u(x,t)}{\partial x}dx \qquad (3)$$

$$\varepsilon = \partial u(x,t)/\partial x \,, \qquad (4)$$

and the force F_t impact on the cross section of pipe can be written as:

$$F_t(t,x) = E_0 A\frac{\partial u}{\partial x} + C_D A\frac{\partial^2 u}{\partial t \partial x} - F_{mag}, \qquad (5)$$

the dynamic equation for the piece is as follow:

$$\frac{\partial F_t}{\partial x} = \rho A\frac{\partial^2 u}{\partial^2 t}, \qquad (6)$$

From the one-dimensional nonlinear constitutive relations defined in Eq.(1) and mechanics of materials, the magneto-mechanical force F_{mag} is given by:

$$F_{mag} = \nabla \cdot (e \cdot \overline{H}) = e_{k,ij}(\partial H_k / \partial x_j), \qquad (7)$$

where

$$e_{k,ij} = \left(\frac{\partial \sigma_{ij}}{\partial H_k}\right) = \left(\frac{\partial \sigma_{ij}}{\partial \varepsilon_{mn}}\right)_{|H=0}\left(\frac{\partial \varepsilon_{mn}}{\partial H_k}\right)_{|\sigma=0}, \qquad (8)$$

and the natural boundary condition is given as follows:

$$u(0,t) = 0 \qquad (t \geq 0), \qquad (9)$$

$$y(0,x) = 0, \quad \frac{\partial y}{\partial t}(0,x) = 0 \qquad (x \geq 0), \qquad (10)$$

2.3. Finite Element Model

In the above mentioned, the structural dynamics model is set up by equation of (5) to (9). And the vibration of the pipe could be obtained via structural dynamics model. Noting that the equation of vibration (4) and (5) has variable coefficient with time t, so the Calerkin FEM discretion method is used to solve the problem and the vibration displacement vector can written as :

$$u_{k+1} = \left[I - \frac{\Delta t}{2}A\right]^{-1}\left[I + \frac{\Delta t}{2}A\right]u_n + \left[I - \frac{\Delta t}{2}A\right]^{-1}B\Delta t, \qquad (11)$$

$$A = \begin{bmatrix} 0 & 1 \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, \qquad (12)$$

$$B = \begin{bmatrix} 0 \\ M^{-1}(f_{mag}) \end{bmatrix}, \qquad (13)$$

where the consistent mass matrix of inertia M and the vector of equivalent nodal forces f_{mag} is defined by (14-17).

$$M = \frac{l_r \rho A}{3N}\begin{pmatrix} 2 & 1/2 & 0 \\ 1/2 & \ldots & 1/2 \\ 0 & 1/2 & 1 + \frac{3N}{l_r \rho A}M_{l_r} \end{pmatrix}_{N \times N}, \qquad (14)$$

$$C = \frac{NC_D A}{l_r}\begin{pmatrix} 2 & -1 & 0 \\ -1 & \ldots & -1 \\ 0 & -1 & 1 + \frac{l_r}{NC_D A}C_{l_r} \end{pmatrix}_{N \times N}, \qquad (15)$$

$$K = \frac{NE_0 A}{l_r}\begin{pmatrix} 2 & -1 & 0 \\ -1 & \ldots & -1 \\ 0 & -1 & 1 + \frac{l_r}{NE_0 A}K_{l_r} \end{pmatrix}_{N \times N}, \qquad (16)$$

$$f(\mathbf{t}) = -\vec{f}_{\mathbf{mag}} = \int_0^{l_r}\left(-F_{mag}\phi_i\right)dx, \qquad (17)$$

According to the Eq.(11), we can obtain the displacement of ferromagnetic particle generated by external excitation magnetic field during magnetostriction effect that is the initial impulse of the magnetostriction guided wave.

3. Numerical Simulation and Results Analysis

3.1. Numerical Simulation Details

The magnetostrictive strain is closely related to the magnetostrictive force (F_{mag}), which is affected by the field consist of static bias magnetic and exciting magnetic field. In the process of magnetization, bias magnetic field provides static working point and exciting magnetic field provides dynamic workspace. So the length of the material will periodical change and the ultrasonic is generated. As a result, analyzing the effect of bias magnetic and exciting magnetic on the particle amplitude is a useful way for improving efficiency.

The 3D model of the MsSs is shown in Fig. 3 and dimensions of pipe are D_{in}=47 mm and D_{out}=51 mm. The magnetic and magnetostrictive parameters for iron are taken from reference [17], where density ρ=7850 kg/m^3 and elastic modulus E=2.04 × 10^{11} pa, the magnetic susceptibility in the initial linear region χ_m=215 and saturation magnetization M_s=1.5×10^6 A/m, domain-wall displacement the magnetization M_{ws}=1.0×10^{6}A/m and maximum strain λ_s=4.17×10^{-6}.

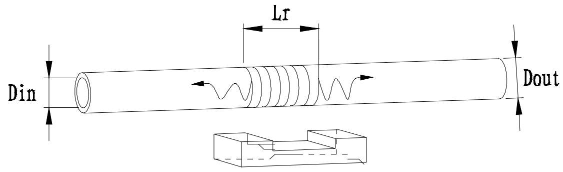

Fig. 3. Three_dimensional model of MsSs.

To study the influence of material magnetizing characteristic on the guided waves excited by MsSs in detail, the outer boundary is set to be a closed boundary and far away from the sources. The static bias magnetic field is known and adjustable and ignoring edge effect of magnetic field generated by the AC coil .The initial value of the variables are zero and the time steps for solving Eq. (11) is 1×10-7s.

Supposing the static bias magnetic field size is H_{bias}, generated by magnet and the exciting magnetic field size is H_{ac}, produced by the coil. So the total magnet field applying on the pipe can be regarded as:

$$H_t = H_{bias} + H_{ac} = H_{bias} + nI\,, \tag{18}$$

In our model, supposing n=20, and the exciting current applied to the coil is the periodical tone burst signal:

$$I(t) = \begin{cases} I_0\left(1-\cos\dfrac{2\pi f_c t}{6}\right)\cos(2\pi f_c t), & 0 \le t \le \dfrac{6}{f_c} \\ 0, & t \ge \dfrac{6}{f_c} \end{cases} \tag{19}$$

where f_c=120 kHz gets from the disperse curve and I_0=1A , the pulse waveform is shown in Fig. 4.

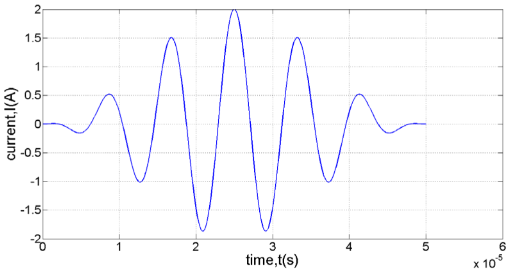

Fig. 4. Exciting pulsed current waveform.

3.2. Results and Discussion

Using the dynamic model, the relation between amplitude of the particle and bias magnetic field is got as Fig. 5. The maximum amplitude is located at the magnetic domain wall moving field. Before the magnetic domain wall moving field, the amplitude increases with the bias magnetic field increases while exceed the field, the amplitude decreases as the field increases and tends to stable finally. The change law of relation between amplitude of the particle and bias magnetic field is the same with the magnetostrictive line, which proving the generation of magnetostrictive guided wave is closely related to the nonlinear characteristics of the magnetic coupling.

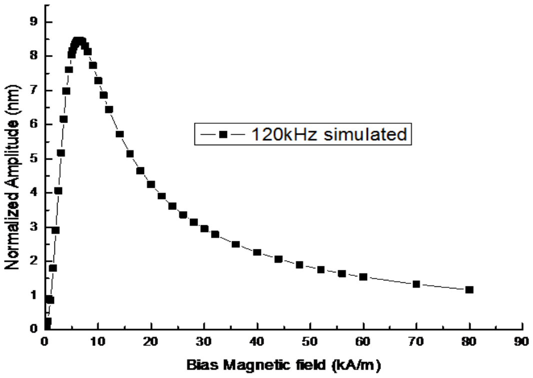

Fig. 5. The relation between amplitude of the particle and bias magnetic field.

The theory behind the magnetostriction and the amplitude of the wave signal is discussed as follows. As discussed earlier magnetostriction process is the resulting strain in a material in the presence of magnetic field. Magnetostriction takes place due to magnetic domain reorientation. A magnetic domain is the region in the material with uniform magnetization i.e. all the atoms within a magnetic domain are grouped together and aligned with one another. In an unmagnetized object though the atoms with in a magnetic domain are aligned in the same direction, the alignment of the atoms changes from domain to domain i.e. different domains point in different directions. When the object becomes magnetized, the all the magnetic domains reorient themselves in the direction of the magnetic field. This magnetic domain reorientation causes a strain in the material. Magnetic reorientation occurs due to two processes. Domains realignment, where the domains that are favorably inclined with the magnetic field growing at the expense of those that are aligned in opposite directions to the field and Rotation magnetization or domain rotation, where the favorably aligned domains rotate into the direction of the magnetic field. Domain realignment occurs at low magnetic fields while the domain rotation takes place at moderate and moderately high magnetic fields.

The effect of current on the particle amplitude is also discussed. As the function of frequency, keeping other parameters as constant, the frequency changes from 20 kHz to 180 kHz in 10 kHz steps. The result is shown in Fig. 6 and the decreasing trend is evident. For static deformation is due to static magnetic field while dynamic magnetic field provides energy for vibrating of particle. When frequencies arising, the particle amplitude has not got the maximum at that field while field starting to decrease, so the particle amplitude cannot reach the maximum. That is the reason for amplitudes decrease with the frequencies increase. The relation between amplitude of the particle and current is explained by Fig. 7. increased.

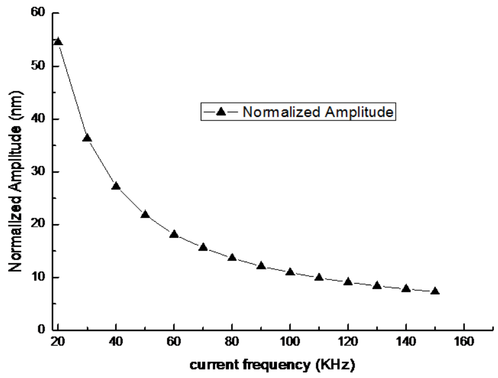

Fig. 6. The relation between amplitude of the particle.

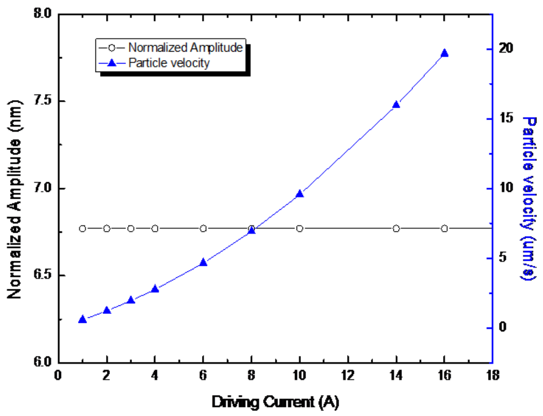

Fig. 7. The relation between amplitude of the particle and current frequency and Driving current.

For bias magnetic is larger than dynamic magnetic by coil, the particle amplitude is affected by current can be neglectable and amplitude keep stable. On the other side, the result also shows that particle velocity increases linearly with the driving current for energy.

4. Conclusions

The coupled magnetostrictive equations often analogized with piezoelectricity in the model of MsSs in past studies, which can only work around the static working point that given before. So the nonlinear coupled magnetostrictive equations are used for the dynamic model of MsSs. By this model, the effect of bias magnetic field, driving current and exciting frequency on the magneto-mechanical coupling performance are discussed. The analysis shows that, with the increasing of bias magnetic, the particle amplitude increases at first than decreases when the field exceeding domain-wall displacement of magnetization. The particle amplitude get small with frequency increased, while the current magnitude has little effect on it. However, the current magnitude can let particle velocity speed-up as current increase. So in order to improve the efficiency of MsSs, as regarding of frequency dispersion, the low frequency and large driving current should be chosen. Moreover, the suitable bias magnetic field is determined by the maximum tangent slope of the amplitude curve.

Acknowledgments

The authors are grateful for the support by the National Natural Science Foundation of China No. 50875077 and the Key Project of Chinese Ministry of Education No. 211110.

References

[1]. K. S. Kumar, V. S. N. Muthy and K. Balasubramaniam, Improvement in the signal strength of magnetostrictive ultrasonic guided wave transducers for pipe inspection using a soft magnetic ribbon-based flux concentrator, *Insight- Non-Destructive Testing and Condition Monitoring*, Vol. 54, Issue 4, 2012, pp. 217-220.

[2]. R. B. Thompson, A model for the electromagnetic generation and detection of Rayleigh and lamb waves, *IEEE Transactions on Sonics and Ultrasonics,* Vol. 25, Issue 12, 1978, pp. 5-7.

[3]. I. V. Il'in and A. V. Kharitionov, Theory of EMA method of detecting Rayleigh waves for ferromagnetic and ferromagnetic materials, *Sov. J. NDT,* Vol. 16, Issue 1, 1980, pp. 549-554.

[4]. A. Wilbrand, EMUS-probes for bulk waves and Rayleigh waves: model for sound field and efficiency calculations, New procedures in nondestructive testing (Proceeding), P. Hooler, *Springer,* Berlin Heidelberg, 1983, pp. 71-80.

[5]. A. Wilbrand, Quantitative modeling and experimental analysis of the physical properties of electromagnetic ultrasonic transducers, in *Proceedings of the Conference on 'Annual Review of Progress in Quantitative Nondestructive Evaluation'*, American, Williamsburg, 21–26 June 1987, pp. 671-680.

[6]. S. Y. Gurevich, The theory of electromagnetic generation of acoustic waves in a ferromagnetic medium at a high temperature, *Russian Journal of NDT,* Vol. 29, 1993, pp. 193-204.

[7]. V. D. Boltachev, L. S. Pravdin and V. G. Kuleev, Electromagnetic-acoustic excitation in ferromagnetic pipes with a circular section, *Russian Journal of NDT,* Vol. 25, 1990, pp. 434-439.

[8]. K. S. Kannsn and A. Dasgup, A nonlinear Galerkin finite-element theory for modeling magnetostrictive smart structures, *Smart Materials and Structures,* Vol. 6, Issue 3, 1997, pp. 341-350.

[9]. H. Kwun, S. Y. Kim, M. S. Choi, Reflection of the fundamental torsional wave from a stepwise thickness change in a pipe, *Journal of the Korean Physical Society,* Vol. 46, Issue 6, 2005, pp. 1352-1357.

[10]. J. Xu J., C. Cheng, X. J. Wu, Equivalent method of bias magnetic field for generating guided waves based on magnetostrictive effect, *J. Huazhong Univ. of Sci. & Tech. (Natural Science Edition),* Vol. 40, Issue 11, 2012, pp. 12-16.

[11]. R. Ribichini, F. Cegla, P. B. Nagy, Quantitative Modeling of the Transduction of Electromagnetic Acoustic Transducers Operating on Ferromagnetic Media. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control,* Vol. 57, Issue 12, 2010, pp. 2808-2817.

[12]. M. S. Choi, S. Y. Kim, H. Kwun, An equivalent circuit model of magnetostrictive transducers for guided wave applications, *Journal of the Korean Physical Society*, Vol. 47, Issue 6, 2005, pp. 454-462.

[13]. M. S. Choi, S. Y. Kim, H. Kwun, Transmission line model for simulation of guided-wave defect signals in piping, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control,* Vol. 51, Issue 5, 2004, pp. 640-643.

[14]. W. Kim and Y. Y. Kim, The effect of the bias magnetic field on the magnetostrictive sensor performance in flexural wave-based damage detection in a cylinder, in *Proceedings of the Conference on 'World Conference on NDT (WCNDT'04)*, Montreal, Canada, 30 August - 3 September 2004, pp. 490-496.

[15]. M. J. Sablik, K. L. Telschow, B. Augustyniak, Relationship between magnetostriction and the magnetostrictive coupling coefficient for magnetostrictive generation of elastic waves, in *Proceedings of the Conference on 'Quantitative Nondestructive Evaluation',* American, Brunswick, Maine, 29 July - 3 Aug 2001, pp. 1613-1620.

[16]. H. M. Zhou, Y. H. Zhou, A Nonlinear Magneto-Mechanical coupling constitutive model for ferromagnetic materials, in *Proceedings of the 5th International Conference on Nonlinear Mechanics (ICNM-V'2007)'*, China, Shanghai, 11-14 June 2007, pp. 236-241.

[17]. X. J. Zheng, L. Sun, A nonlinear constitutive model of magneto-thermo-mechanical coupling for giant magnetostrictive materials, *Journal of Applied Physics*, Vol. 100, Issue 6, 2006, pp. 063906 - 063906-6.