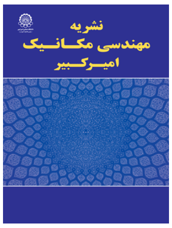

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Study of Nonlinear Vibration Behavior of an Electric Current-Carrying Ferromagnetic Plate in Magnetic Field

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ABSTRACT: In the present study, considering the magnetic tractions and heat generated by electric current and eddy current, new nonlinear equations have been proposed to investigate the vibrational behavior of ferromagnetic plates carrying an electric current under a magnetic field. After extracting the governing differential equations of the system using Newton's second law, the coupled nonlinear equations are discretized using the Galerkin method and then solved numerically. The numerical results presented in the present study are compared with the results in the technical literature and then the effect of different parameters on the vibration characteristics of soft ferromagnetic plates is investigated. The results show that the magnetic field and electric current have a significant effect on the vibration behavior of the plate and lead to an increase in the amplitude oscillations of the system. The presence of a magnetic field reduces the equivalent stiffness of the plate and increases it, resulting in static instability in the system. Also, by considering the force created by magnetic tractions, a static rise is created in the plate and affects its steady-state response. In the study of thermal effects, it was found that the assumption of thermal coupling increases the natural frequency of the plate.

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1- Introduction

Electromagnetic solids include a wide range of materials and the interaction of mechanical and electromagnetic loads has a significant effect on their deformation. In most cases, the behavior of electromagnetic materials is described by a system of motion equations and Maxwell equations.

In the present paper, considering the interaction between a ferromagnetic material and magnetic field, magnetic tractions, and the temperature generated by electric currents, new thermo-magneto-electro-mechanical equations are obtained to study the transverse vibration behavior of ferromagnetic beams located in the magnetic field. The effect of electric current is presented. For this purpose, motion equations have been extracted using strain-displacement relations and equilibrium equations. Then, by applying the Galerkin method and numerical solution of the obtained coupling equations, the effect of different parameters on the vibrational behavior of these plates has been studied.

2- Methodology

According to Fig. 1, the isotropic conduction plate is considered to be the length a, the width b, and the thickness h, which carries the electric current along the x-axis and is affected by the intensity of the inclined magnetic field B_0.

According to Maxwell's classical relations, Maxwell's electromagnetic stress tensor is obtained as follows [1]:

$$\sigma_{ij}^{Maxwell} = \varepsilon_0\left(E_iE_j - \frac{1}{2}\delta_{ij}E^2\right) + \frac{1}{\mu_0}\left(B_iB_j - \frac{1}{2}\delta_{ij}B^2\right) \tag{1}$$

3- Equations of Motion

Using the assumptions of the plate-strip theory, the classical plate theory is used to derive the governing equations. And the differential equations of motion are obtained by the results of flexural moments affected by electromagnetic force, magnetic couplings, and magnetic tractions as follows.

$$\begin{aligned} & -\frac{Eh^3}{12\left(1-\nu^2\right)}\frac{\partial^4 w}{\partial x^4} \\ & -\left[\frac{1}{4\mu_0\left(1+\chi_m\right)}\begin{pmatrix} h^2J^2\mu_0^2\left(1+\chi_m\right)^2\left(-1+2\chi_m\right) \\ +B_0^2\left(-4+8\chi_m^2\right)\end{pmatrix}\frac{\partial w}{\partial x}\right]\frac{\partial w}{\partial x} \\ & +\left[\frac{1}{4\mu_0\left(1+\chi_m\right)}\begin{pmatrix} h^2J^2\mu_0^2\left(1+\chi_m\right)^2\left(-1+2\chi_m\right) \\ +B_0^2\left(-4+8\chi_m^2\right)\end{pmatrix}\left(\int_0^x\frac{\partial w}{\partial x}dx - \frac{1}{L}\int_0^L\int_0^x\frac{\partial w}{\partial x}dxdx\right)\right. \\ & \left.+\frac{1}{2l}\frac{Eh}{1-\nu^2}\int_0^l\left(\frac{\partial w}{\partial x}\right)^2dx\right]\frac{\partial^2 w}{\partial x^2} + t_z^{EM} + \frac{\partial C_y}{\partial x} = \rho h\frac{\partial^2 w}{\partial t^2} - \rho h^3\frac{\partial^4 w}{\partial x^2\partial t^2} \end{aligned} \tag{2}$$

Also, using the classical Fourier heat transfer model,

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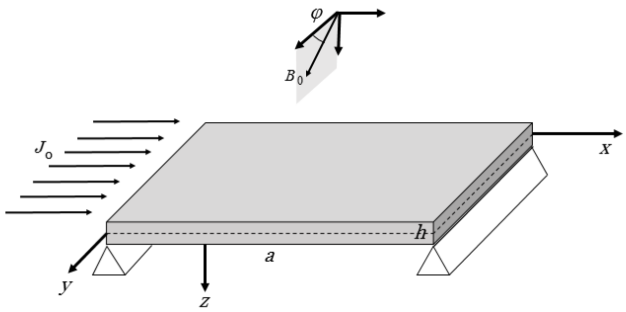

Fig. 1. The ferromagnetic thin plate under the influence of magnetic field and electric current

Table 1. Changes in the free vibration frequency of a cantilever plate under a magnetic field to the magnetic field intensity

B(mT)	present study	Wei et al. [5] Percentage of the Error (%)	Takagi et al.[4] Percentage of the Error (%)
0	40.900	42.15(0.029%)	41.91(0.024%)
0.20	41.837	43.032(0.027%)	47.01(0.110%)
0.40	42.808	43.882(0.024%)	51.02(0.160%)
0.60	44.328	44.757(0.009%)	52.98(0.163%)
1.00	45.934	46.164(0.004%)	54.98(0.164%)

the energy equation of the conduction heat transfer [2, 3] is extracted as follows:

$$k\frac{\partial^2\theta}{\partial x^2} = \left(\rho C_v + \gamma E\alpha^2 T_0\right)\frac{\partial\theta}{\partial t} + \left(3\lambda + 2G\right)\alpha T_0\frac{\partial}{\partial t}\left(\frac{\partial u_0}{\partial x}\right) + \frac{J_0^2}{\sigma}\left(\frac{1+2\chi_m}{1+\chi_m}\right)^2 \quad (3)$$

The above equation expresses the relationship between displacement-temperature fields based on the theory of thermoelasticity for isotropic material under the influence of heat.

4- Solution of the Governing Equation

In order to solve the governing equations which are nonlinear equations, the Galerkin method is used. For this purpose, the following expansions are considered for the field of elastic displacement and temperature distribution [6]:

$$\eta(\xi,\tau) = \sum_{i=1}^{R} q_i(t)\psi_i(\xi), \qquad \Theta(\xi,\tau) = \sum_{i=1}^{R}\Theta_i(t)\phi_i(\xi) \quad (4)$$

By placing hypothetical answers in the equations of motion and energy, the partial differential equations are discretized as differential equations with ordinary derivatives, in which the unknown functions of the generalized coordinates can be calculated. And the time response of the system will have obtained for different values of system parameters.

5- Results and Discussion

In the present paper, in order to enable the comparison of the results with the experimental results, the geometric characteristics of the ferromagnetic plate are presented in Table 1. The results show that with increasing the intensity of the magnetic field, the frequency of the system increases.

In the following, the effect of different parameters on the vibrational characteristics of ferromagnetic plates is studied. Fig2 . shows the effect of magnetic field intensity on the frequency response of the ferromagnetic plate with simple supports at both ends for current $J0$ = 2A. As can be seen, the magnetic field has a significant effect on the vibrational behavior of the structure and with increasing the intensity of the magnetic field, the amplitude of system oscillations also increases.

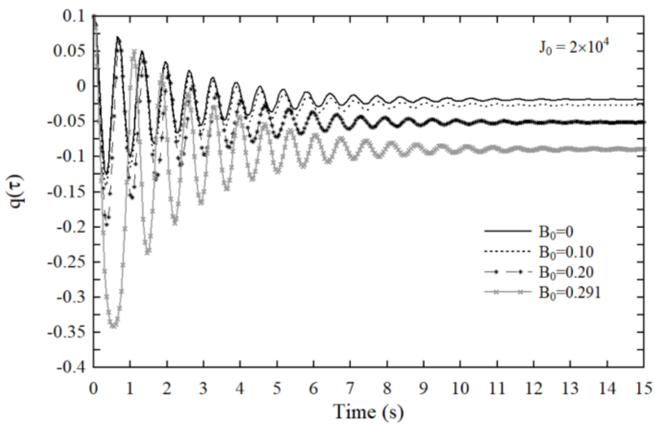

Fig. 2. Effect of magnetic field intensity on the frequency response of a ferromagnetic plate with simple supports at both ends for current J0 = 2 A

6- Conclusions

In the present paper, considering the effects of magnetic tractions and eddy currents as well as the heat generated by electric currents, new mechanical-magnetic-thermal equations were presented to study the dynamic behavior of soft ferromagnetic plates. Discrete equations were studied using the Galerkin method and then the effect of different parameters on the vibrational characteristics of these systems was studied using the numerical solution. The results of the present study show that the component of the force created by magnetic tractions causes a change in the vibrational characteristics of the plate.

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