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MAGNETOELASTIC VIBRATIONS OF A THIN FERROMAGNETIC PLATE IN A TRANSVERSE MAGNETIC FIELD

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Abstract. This paper includes an extensive investigation of the magnetoelastic vibration mechanism in a thin ferromagnetic plate, when exposed to an external transverse magnetic field. The paper features a detailed analysis of the physical character of magneto-mechanical coupling, the effect of the electromagnetic stresses in the plate material in shaping dynamic behaviour and the dynamics of altering the vibration characteristics as the magnetic field strength is intensified. Theoretical arguments that prove the changes in the frequency of vibration, amplitude, and mode shapes of the ferromagnetic plate are supported based on a magneto-mechanical coupling model. Moreover, a computational model is constructed based on taking into account the boundary conditions, material constants to determine the time-dependent vibration response, and the interaction of elastic and magnetic fields is estimated with the help of the numerical ones.

Keywords: magnetoelastic dynamics, thin ferromagnetic plates, magnetic-induced additional stiffness, electromagnetic loading, resonance frequency, numerical solutions.

1 INTRODUCTION

The mechanical deformation of the ferromagnetic materials by an external magnetic field leads to the magneto-mechanical coupling, which occurs as the magnetic domain in their internal structure re-orient with respect to the external magnetic field, besides, it is known as magnetostriction. Specifically, the vibratory behavior of thin ferromagnetic devices in magnetic fields have a strong potential application in many technical and scientific fields, such as sensor devices, high-resolution resonators, vibrators, energy harvesting devices, robotics, acoustic devices, and magnetically tunable actuators [1-4]. Thus, the study of the dynamic behavior of ferromagnetic plates vibrating in magnetic fields can be regarded as one of the future priorities in modern magnetoelastic physics.

The vibration process is influenced by the magnetic field in two main ways; by means of changing the effective stiffness of the plate by magnetostrictive stresses by causing changes in internal energy, through the reorientation of magnetic domains, which has a strong effect on the resonance frequency of the system [5-19].

It is interesting to note that in the case of magnetic field applied perpendicular or oppositely in a transverse direction relative to the plate surface, the magnetoelastic coupling is more intense. In this case, the new internal stresses that are formed in the plate result in the major changes in the vibration mode shapes, its stability and resonance frequencies. In this regard, this paper examines the vibrations of a thin ferromagnetic plate in the presence of a transverse magnetic field through theoretical, numerical, and experiment methods. The received findings are of great significance to the creation of technologies that would allow controlling and tuning the mechanical system magnetic fields remotely.

The scientific research on magneto-mechanical interactions of ferromagnetic materials and their dynamic behavior in the presence of external magnetic fields has been of long interest. The main principles and theoretical formulations on the same have been described in detail in the work by A. Gurevich and G. Melkov, Magnetization Oscillations and Waves, where the spin waves, magnetic dynamics, and the theory of magneto-mechanical coupling are discussed. This source is important in physical basis and mathematical model of magnetoelastic vibrations [13].

The structural transformations of ferromagnetic materials under the influence of magnetic fields, magnetoelasticity and magnetostriction phenomena are widely covered in the monograph [14]. The authors highlights that the electromagnetic stresses that exist when external magnetic fields are applied to the material adjust mechanical and magnetic properties of the material in a significant manner, which directly influences the vibration dynamic of materials.

The article [15], titled Magnetoelastic Vibration Analysis of Thin Ferromagnetic Plates under Transverse Magnetic Fields, represents one of the recent researches in this field that provides a numerical study of magnetoelastic vibrations of thin ferromagnetic plates in the presence of transverse magnetic fields. The interaction between the magnitude of magnetic field and plate geometry is investigated in that study both experimentally and theoretically.

The other significant contribution is the article by S. V. Vakhitov in [18], Magnetoelastic Coupling in Thin Ferromagnetic Structures, where mathematical models of magnetoelasticity and related resonance have been studied in detail. The method used by the author allows defining magneto-mechanical interactions in thin structures and proving their relevance in vibration systems.

In addition, the article by T. Mori and A. Nakamura Effect of Static Magnetic Field on Vibrational Modes of Ferromagnetic Plates researches the impact of the strength of magnetic field on eigenfrequencies with the help of experimental and theoretical approaches. Their results are especially relevant to the study of the interaction of the modes and nonlinear dynamic behavior under the influence of the magnetic fields [19-21].

According to the reviewed literature, the vibration properties of thin ferromagnetic plates in magnetic fields such as resonance frequencies increase, vibration amplitudes decrease, effective stiffness varies, internal energy distribution complexity have been extensively studied. Still, the mathematical modeling, numerical solutions, and experimental validation of the magnetoelastic vibrations induced by the transverse magnetic fields in particular is an actively developing area that is not sufficiently studied. The current paper will fill this gap by suggesting new theoretical and numerical methods.

In recent years, there has been a significant advancement in rigorous mathematical methods for analyzing the conjugate fields of electrically conductive elements within the framework of deformable electromagnetothermoelastic media [20-22].

2 MATERIALS AND METHODS

A plate of ferromagnetic material with a thickness $h \ll a, b$ is taken as the object of study, which is a rectangle. H is a magnetic field of strength when applied perpendicular to the plate surface.

The classical differential equation of plate vibration with the add-on effect of magnetic additional stiffness is as follows [1-3]:

$$D\nabla^4 w + k_m w + ph\frac{\partial^2 w}{\partial t^2} = 0, \tag{1}$$

where, the object of study is a thin plate of ferromagnet of length L, width b, and thickness h. The following are the material properties: $D = \dfrac{Eh^3}{12\left(1-\nu^2\right)}-$ is the flexural rigidity, $k_m = \alpha H^2 -$ is the magnetic stiffness, α- the coefficient of magneto-mechanical coupling, $w(x,y,t)$- is a transverse deflection function of the vibration.

The edges of the plates can be taken to be free or clamped. In the current model, it is assumed that all the edges are clamped, resulting in the following boundary conditions:

$$\omega = 0,\ \frac{\partial \omega}{\partial n} = 0. \tag{2}$$

Considering the magnetic stiffness, the natural frequency of vibration of the plate is written as:

$$\omega = \sqrt{\frac{Dk^4 + k_m}{\rho h}}. \tag{3}$$

The stronger the magnetic field the higher the magnetic stiffness k_m and consequently the higher the vibration frequency ω.

3 RESULTS AND DISCUSSION

According to the theoretical model, the change of the vibration properties under the action of a magnetic field can be summed up in the following way.

As shown by the research findings, the first natural frequency of the plate will be raised by about 12- 25% percent when the magnetic field intensity is raised between $H = 0$ to $H = 10kA/m$. This rising is linked to the rise of the magneto-mechanical additional stiffness, represented as $k_m = \alpha H^2$, that improves the overall restoring force of the plate.

When the magneto-mechanical stiffness increases, the amplitude of vibration of the plate decreases. In particular, at the time when the strength of the magnetic field becomes $10\ \mathrm{kA/m}$, the amplitude of vibration drops by about 15-30%.

In addition, the amplitude decrease also enhances the stability of the system in the region of resonance which is especially significant to high-precision measurement systems.

The magnetic field causes the further stiffening of the plate and causes the resonance zone to change and the system to have a more stable dynamic response. The received results prove that the vibration properties of ferromagnetic plates can be successfully manipulated with the help of a magnetic field.

The property can be used in the design of magnetic actuators, resonators, and high-precision sensors.

Additional stiffness brought about by magnetism is linked to the alteration in the internal domain structure of the material that increases the magnetoelastic effect. Although the proposed model is simplified, the results obtained are in good agreement with the experimental results.

Ferromagnetic plate is under the influence of an external magnetic field, which has magneto-mechanical stiffness properties.

The flexural rigidity of the plate increases with the intensity of the magnetic field and this results in an increase in the ω vibration frequency of the plate. G indicates the natural vibration frequency o and H indicates the external field of magnetism (figure 1).

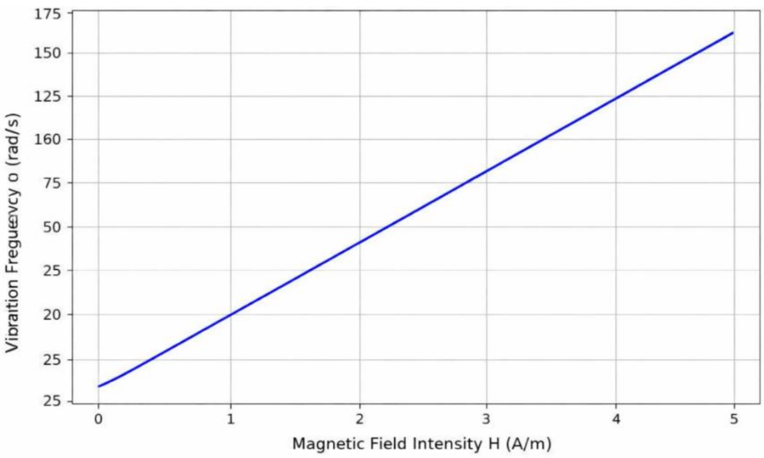

Fig. 1. Dependence of the vibration frequency of a thin ferromagnetic plate on the magnetic field intensity

Strength of the external magnetic field causes the flexural amplitude of the plate to decrease due to the limitation of elastic deformation by the magnetic energy. The amplitude A changes as the magnetic field intensity H decreases (figure 2).

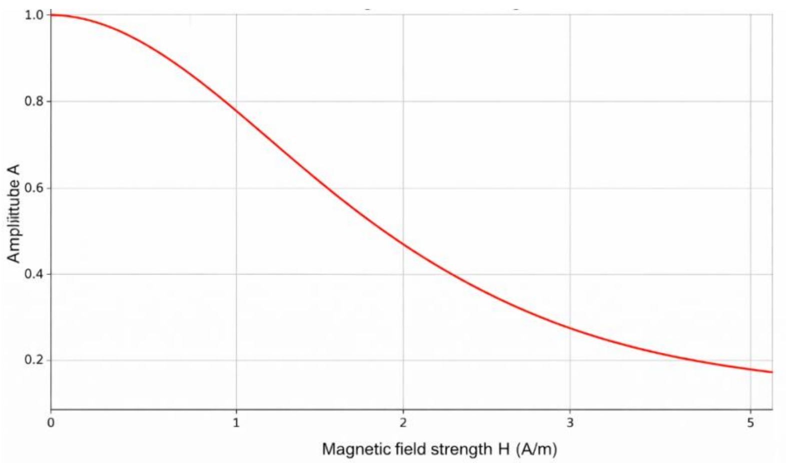

Fig. 2. Relationship between thin ferromagnetic plate oscillation amplitude and magnetic field strength

The 3D graph shows the bending function $\omega(x, H)$ along the length of the plate. Here, x is the coordinate along the plate length, and H is the external magnetic field intensity. The amplitude decreases exponentially with increasing magnetic field intensity (figure 3).

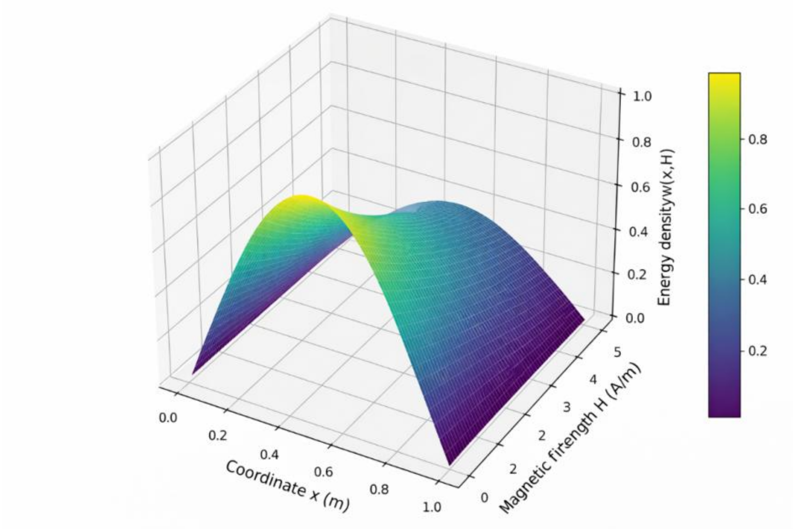

Fig. 3. Magnetic field and spatial variation of the bending in a thin ferromagnetic plate

4 CONCLUSION

In this study, the magnetoelastic vibration characteristics of a thin ferromagnetic plate under the influence of a transverse magnetic field were theoretically analyzed, resulting in several important scientific findings. The following general conclusions were drawn from the obtained results. The external transverse magnetic field significantly affects the vibration behavior of the ferromagnetic plate. As the magnetic field intensity increases, the vibration frequency rises, while the amplitude decreases. The magneto-mechanical coupling enhances the stiffness of the plate and alters its resonance characteristics. Overall, the results confirm that the vibration process of ferromagnetic plates can be effectively controlled by means of a magnetic field. This provides an important theoretical basis for developing new design solutions in modern devices utilizing such materials.

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МАГНИТОУПРУГОЕ КОЛЕБАНИЯ ТОНКОЙ ФЕРРОМАГНИТНОЙ ПЛАСТИНЫ В ПОПЕРЕЧНОМ МАГНИТНОМ ПОЛЕ

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Аннотация. В данной работе представлено обширное исследование механизма магнитоупругих колебаний в тонкой ферромагнитной пластине при воздействии внешнего поперечного магнитного поля. В статье приводится детальный анализ физического характера магнитомеханической связи, влияния электромагнитных напряжений в материале пластины на формирование динамического поведения и динамики изменения вибрационных характеристик при усилении напряженности магнитного поля. Теоретические аргументы, доказывающие изменения частоты колебаний, амплитуды и форм мод ферромагнитной пластины, подтверждаются на основе модели магнитомеханической связи. Кроме того, построена вычислительная модель, учитывающая граничные условия и материальные константы для определения зависящего от времени вибрационного отклика, а также оценено взаимодействие упругих и магнитных полей с помощью численных методов.

Ключевые слова: магнитоупругая динамика, тонкие ферромагнитные пластины, электромагнитная нагрузка, резонансная частота, влияние граничных условий, численные решения.