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Critical multi-field load analysis of the piezoelectric/piezomagnetic microplates as an application in sports equipment

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Abstract. Critical multi-field loads and free vibration responses of the sandwich piezoelectric/piezomagnetic microplate subjected to combination of magnetoelectromechanical loads based on a thickness-stretched higher order shear deformable model using Hamilton's principle. The lateral displacement is assumed summation of bending, shearing and stretching functions. The elasti core is sandwiched by a couple of piezoelectric/piezomagnetic face-sheets subjected to electromagnetocmechanical loads. The work of external force is calculated with considering the in-plane mechanical, electrical and magnetic loads based on piezomagnetoelasticity relations. The critical multi field loading and natural frequency analysis are performed to investigate influence of geometric and loading parameters on the responses. A verification is performed for justification of the numerical results.

Keywords: Hamilton's principle; higher-order modelling; multi-field loading; sandwich piezoelectric/piezomagnetic microplate, scale-dependent model

1. Introduction

More accurate analysis of sandwich and composite structures are performed using the higher-order shear deformation theory. It is confirmed that the out of plane normal strains has a significant effect on the bending, buckling and vibration responses of sandwich structures made of piezoelectric and piezomagnetic materials in various situations as an element of electromechanical systems. Sensor and actuator applications of the intelligent sandwich structures are developed in the references (Civalek 2014, Ersoy *et al*. 2018, Civalek and Baltacioglu 2019, Civalek *et al*. 2011, Arefi and Civalek 2020, Habibi *et al*. 2019, Mercan and Civalek 2019, Ghabussi *et al*. 2021). Combination of this topic with new advanced size dependent theory yields an innovative analysis in the scope of mechanical engineering and multi-field loadings. A literature survey is presented for justification of the necessity of this concept in the context of mechanical engineering.

Katariya *et al*. (2021) developed an excellent experimental and theoretical work on the modal analysis of a sandwich structure filled with epoxy based on higher-order theory including thickness stretching for a variable thickness structure. They summarized importance and efficiency of the proposed theoretical work to modal analysis of composite structure with skew angle effect. Chaht *et al*. (2015) studied influence of functionality as well as thickness stretched model on the bending and buckling responses of a small scale nanobeam based on accounting out of plane normal strain. Impact of stretching and variable material properties was investigated on the bending and stability responses. Chalak (2019) investigated effect of multi field loading, material and geometric parameters on the various mechanical behaviours of laminated sandwich/ composite structures based on different lower and higher order theories. Mulmule and Rath (1993) extended a new multi director displacement field method for analysis of sandwich structures to arrive an optimized geometrical and material composition for sandwich structures based on out of plane normal strain included theories. Efficiency of the multi director field was confirmed using comparison with finite element approach results. Carrera *et al*. (2011) developed a comprehensive theoretical model accounting thickness stretching for analysis of the plates/shells based on Unified formulation proposed by Carrera. Accuracy and importance of the excellent theory was justified with comparing the results with and without stretching function. The new and efficient higher order shear deformation theories was studied for static and dynamic analyses of advanced materials and structures by Liu *et al*. 2022, Van Vinh *et al*. 2022a, b, Faghidian *et al*. 2022, Garg *et al*. 2022, Le *et al*. 2022, Vinh and Tounsi 2022a, b, Tahir *et al*. 2022, Bouafia *et al*. 2021. The effect of porous material and nanofillers was studied on the bending and vibration responses of advanced materials and structures by Huang *et al*. 2021, Kumar *et al*. 2021, Arshid *et al*. 2022, Heidari *et al*. 2021, Rouabhia *et al*. 2020, Katiyar *et al*. 2022, Djilali *et al*. 2022. Dinh Duc and Hong Cong (2018) studied effect of nonlinear strain on the dynamic and vibration analyses of sandwich plates based on higher order modelling. Hong Cong and Dinh Duc (2023) investigated influence of Kerr foundation and nonlocality on the nonlinear static and dynamic responses of small scale plate reinforced with graphene nanoplatelets. One can finds new composite production methods reported by Zhang *et al*. 2022a, b, Luo

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et al. 2023, Peng *et al*. 2020, Muhammad *et al*. 2022, Lu *et al*. 2021, 2022a, b, Dang *et al*. 2023, Yang *et al*. 2021, 2022 a, b, Hu *et al*. 2022, Li *et al*. 2023, Hou *et al*. 2023, Lu *et al*. 2022c, Fan *et al*. 2020, Ren *et al*. 2022.

Sarvestani *et al*. (2018) extended a comprehensive investigation for determination of the preferred geometry of three dimensional meta sandwich structure. It was concluded that the structures composed of isomax metamaterial cores reflects a higher level for energy absorption. Kim and Park (2021) employed an orthogonal decomposition as well as automatic machine learning for multi-disciplinary optimization of a wing sandwich structure based on a reduced order model. Application of the proposed optimization method was used for effect of stretching on the sandwich structure as a wing skin of aircraft. Ottavio *et al*. (2021) studied free/forced analyses of a sandwiched beam and plate subjected to damping force based on zener model. The solution was obtained based on an efficient Ritz method to satisfy boundary conditions. The effect of out of plane normal strain was studied on the frequency responses using a direct scheme and modal projection algorithm. Carrera *et al*. (2017) employed a variable thickness element with capability of thickness stretching for analysis of sandwich and composite structures based on unified formulation developed by Carrera. They presented efficiency of the proposed method in reducing the costs of the computational methods. Mathew *et al*. (2011) used finite element method considering nonlinear strain components for optimization of the multi-layer structures with discussion on the energy absorption. Damping characteristics of a sandwich structure based on finite element method and FSDT as well as zigzag theory were studied by Adessina *et al*. (2016). It was concluded that the index of rigidity of the structure is linearly changed with thickness of viscoelastic face-sheets and quadratically with core thickness. George and Kardomateas (2018) presented a review work on the new design method and novel application of sandwich structures made of FGM applicable in various situations such as marine engineering, aerospace and civil engineering.

Gao and Sun (2015) developed a control strategy for composite sandwich structures including lattice truss core in thermal environment and water convection. The fin theory and resistance network method were used for thermal analysis of the structure. Hu *et al*. (2008) studied mechanical behaviour of the sandwich and composite structures based on Arlequin multi scale method. For this purpose, a clamped free beam composed of soft core was used for validation of the theory. Talebitooti *et al*. (2021) extended a multi objective optimization method for acoustical vibration behavior of double walled composite shell in doubly curved geometry composed of poroelastic material based on genetic algorithm. The main importance of this work was design of the algorithm for improvement of acoustical vibration fitness and doubly curved weight. Georgiou (2008) studied nonlinear coupled dynamical analysis of sandwich structure composed of a honeycomb core based on orthogonal decomposition modes. The geometric nonlinearity was accounted through finite element scheme. The structure was subjected to blast load and a harmonic force. He *et al*. (2011) developed a multi scale method for analysis of the sandwich structures based on lower and higher order elements through unified formulation proposed by Carrera and Arlequin framework. A higher order polynomials approximation was used for the unknown displacements. Yu *et al*. (2013) studied wrinkling and buckling analyses of the sandwich structures based on Fourier-related analysis.

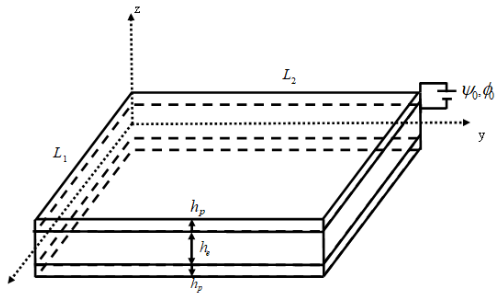

Fig. 1 The schematic figure of a sandwich microplate

Recent works on the vibration, buckling and multi field analyses of shear deformable sandwich microplate was completed in this section. The review indicates that there is no published work on the multi field critical load and free vibration analyses of the sandwich piezoelectric/piezomagnetic microplates. In this work, a higher-order thickness stretched shear deformable model is used for the multi-field analysis. The main novelty of this work is concurrent accounting the out of plane normal and shear strains and stresses and multi filed loading on the multi-field responses of the sandwich microplate.

2. Thickness-stretched Formulation of a sandwich piezoelectric/piezomagnetic microplate

Multi-field modeling of a sandwich piezomagnetic microplate is studied in this section using a thickness stretched model including bending, shear and stretching function in displacement field as follows (Arshid *et al*. 2022):

$$\begin{gathered} u_x = u_0 - z\frac{\partial w_b}{\partial x} - f(z)\frac{\partial w_s}{\partial x}, \\ v_y = v_0 - z\frac{\partial w_b}{\partial y} - f(z)\frac{\partial w_s}{\partial y}, \\ w_z = w_b + w_s + g(z)\chi \end{gathered} \tag{1}$$

In which w_b, w_s, χ are denoted as bending, shear and stretching parts of deflection (Fig. 1).

The kinetic energy variation is defined as (Arshid *et al*. 2022):

$$\delta T = \int_{x_1}\int_{x_2}\int_{z} \begin{gathered} [\left(\dot{u}_0 - z\frac{\partial \dot{w}_b}{\partial x} - f(z)\frac{\partial \dot{w}_s}{\partial x}\right) \\ \left(\delta\dot{u}_0 - z\frac{\partial \delta\dot{w}_b}{\partial x} - f(z)\frac{\partial \delta\dot{w}_s}{\partial x}\right) \\ + \left(\dot{v}_0 - z\frac{\partial \dot{w}_b}{\partial y} - f(z)\frac{\partial \dot{w}_s}{\partial y}\right) \\ \left(\delta\dot{v}_0 - z\frac{\partial \delta\dot{w}_b}{\partial y} - f(z)\frac{\partial \delta\dot{w}_s}{\partial y}\right) \\ + (\dot{w}_b + \dot{w}_s + g(z)\dot{\chi})(\delta\dot{w}_b + \delta\dot{w}_s + g(z)\delta\dot{\chi})] \end{gathered} dV \tag{2}$$

Definition of integration constants $J_i = \int_{-\frac{h_e}{2}-h_p}^{\frac{h_e}{2}+h_p} \rho z^i dz$, $i = 0..2$, $J_3 = \int_{-\frac{h_e}{2}-h_p}^{\frac{h_e}{2}+h_p} \rho f(z) z^0 dz$, $J_4 = \int_{-\frac{h_e}{2}-h_p}^{\frac{h_e}{2}+h_p} \rho f(z) z^1 dz$, $J_5 = \int_{-\frac{h_e}{2}-h_p}^{\frac{h_e}{2}+h_p} \rho f(z) f(z) dz$, $J_6 = \int_{-\frac{h_e}{2}-h_p}^{\frac{h_e}{2}+h_p} \rho g(z) z^0 dz$, $J_7 = \int_{-\frac{h_e}{2}-h_p}^{\frac{h_e}{2}+h_p} \rho g(z) g(z) dz$ simplifies variation of kinetic energy as:

$$\begin{aligned}\delta T = \iint [\Big(&-J_0\ddot{u}_0 + J_1\frac{\partial \ddot{w}_b}{\partial x} + J_3\frac{\partial \ddot{w}_s}{\partial x}\Big)\delta u_0 + \Big(-J_0\ddot{v}_0 + J_1\frac{\partial \ddot{w}_b}{\partial y} + J_3\frac{\partial \ddot{w}_s}{\partial y}\Big)\delta v_0 + \Big(-J_1\frac{\partial \ddot{u}_0}{\partial x} + J_2\frac{\partial^2 \ddot{w}_b}{\partial x^2} + J_4\frac{\partial^2 \ddot{w}_s}{\partial x^2} - J_1\frac{\partial \ddot{v}_0}{\partial y} + J_2\frac{\partial^2 \ddot{w}_b}{\partial y^2} + \\ &J_4\frac{\partial^2 \ddot{w}_s}{\partial y^2} - J_0\ddot{w}_b - J_0\ddot{w}_s - J_6\ddot{\chi}\Big)\delta w_b + \Big(-J_3\frac{\partial \ddot{u}_0}{\partial x} + J_4\frac{\partial^2 \ddot{w}_b}{\partial x^2} + \\ &J_5\frac{\partial^2 \ddot{w}_s}{\partial x^2} - J_3\frac{\partial \ddot{v}_0}{\partial y} + J_4\frac{\partial^2 \ddot{w}_b}{\partial y^2} + J_5\frac{\partial^2 \ddot{w}_s}{\partial y^2} - J_0\ddot{w}_b - J_0\ddot{w}_s - \\ &J_6\ddot{\chi}\Big)\delta w_s + (-J_6\ddot{w}_b - J_6\ddot{w}_s - J_7\ddot{\chi})\delta\chi]\, dA\end{aligned} \quad (3)$$

In Cartesian coordinate system, the strain components are obtained as:

$$\begin{aligned}\varepsilon_{xx} &= \frac{\partial u_0}{\partial x} - z\frac{\partial^2 w_b}{\partial x^2} - f(z)\frac{\partial^2 w_s}{\partial x^2},\\ \varepsilon_{yy} &= \frac{\partial v_0}{\partial y} - z\frac{\partial^2 w_b}{\partial y^2} - f(z)\frac{\partial^2 w_s}{\partial y^2},\\ \varepsilon_{zz} &= g'(z)\chi\\ \gamma_{xy} &= \frac{\partial u_0}{\partial y} + \frac{\partial v_0}{\partial x} - 2z\frac{\partial^2 w_b}{\partial x \partial y} - 2f(z)\frac{\partial^2 w_s}{\partial x \partial y},\\ \gamma_{xz} &= g(z)\left(\frac{\partial w_s}{\partial x} + \frac{\partial \chi}{\partial x}\right),\\ \gamma_{yz} &= g(z)\left(\frac{\partial w_s}{\partial y} + \frac{\partial \chi}{\partial y}\right),\end{aligned} \quad (4)$$

The stress components for elastic core are derived as (Arshid *et al*. 2022)

$$\begin{Bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \tau_{yz}\\ \tau_{xz}\\ \tau_{xy}\end{Bmatrix} = \frac{E}{(1-2\vartheta)(1+\vartheta)} \begin{bmatrix}1-\vartheta & \vartheta & \vartheta & 0 & 0 & 0\\ \vartheta & 1-\vartheta & \vartheta & 0 & 0 & 0\\ \vartheta & \vartheta & 1-\vartheta & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1-2\vartheta}{2} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{1-2\vartheta}{2} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{1-2\vartheta}{2}\end{bmatrix} \begin{Bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ \gamma_{yz}\\ \gamma_{xz}\\ \gamma_{xy}\end{Bmatrix} \quad (5)$$

The stress components for integrated piezoelectric/ piezomagnetic face-sheets are derived as (Arshid *et al*. 2022):

$$\begin{Bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \tau_{yz}\\ \tau_{xz}\\ \tau_{xy}\end{Bmatrix} = \begin{bmatrix}C_{xxxx} & C_{xxyy} & C_{xxzz} & 0 & 0 & 0\\ C_{xxyy} & C_{yyyy} & C_{yyzz} & 0 & 0 & 0\\ C_{xxzz} & C_{yyzz} & C_{zzzz} & 0 & 0 & 0\\ 0 & 0 & 0 & C_{yzyz} & 0 & 0\\ 0 & 0 & 0 & 0 & C_{xzxz} & 0\\ 0 & 0 & 0 & 0 & 0 & C_{xyxy}\end{bmatrix} \begin{Bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ \gamma_{yz}\\ \gamma_{xz}\\ \gamma_{xy}\end{Bmatrix} - \begin{bmatrix}0 & 0 & e_{13}\\ 0 & 0 & e_{23}\\ 0 & 0 & e_{33}\\ 0 & e_{42} & 0\\ e_{51} & 0 & 0\\ 0 & 0 & 0\end{bmatrix} \begin{Bmatrix}E_x\\ E_y\\ E_z\end{Bmatrix} - \begin{bmatrix}0 & 0 & q_{13}\\ 0 & 0 & q_{23}\\ 0 & 0 & q_{33}\\ 0 & q_{42} & 0\\ q_{51} & 0 & 0\\ 0 & 0 & 0\end{bmatrix} \begin{Bmatrix}H_x\\ H_y\\ H_z\end{Bmatrix} \quad (6)$$

where E_i, H_i are electric and magnetic field components, respectively. The electric displacement relations for a piezoelectric/piezomagnetic are defined as:

$$\begin{Bmatrix}D_x\\ D_y\\ D_z\end{Bmatrix} = \begin{bmatrix}0 & 0 & 0 & 0 & e_{15} & 0\\ 0 & 0 & 0 & e_{42} & 0 & 0\\ e_{31} & e_{32} & e_{33} & 0 & 0 & 0\end{bmatrix} \begin{Bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ \gamma_{yz}\\ \gamma_{xz}\\ \gamma_{xy}\end{Bmatrix} + \begin{bmatrix}\eta_{11} & 0 & 0\\ 0 & \eta_{22} & 0\\ 0 & 0 & \eta_{33}\end{bmatrix} \begin{Bmatrix}E_x\\ E_y\\ E_z\end{Bmatrix} + \begin{bmatrix}d_{11} & 0 & 0\\ 0 & d_{22} & 0\\ 0 & 0 & d_{33}\end{bmatrix} \begin{Bmatrix}H_x\\ H_y\\ H_z\end{Bmatrix} \quad (7)$$

The magnetic induction relations are extended as:

$$\begin{Bmatrix}B_x\\ B_y\\ B_z\end{Bmatrix} = \begin{bmatrix}0 & 0 & 0 & 0 & q_{15} & 0\\ 0 & 0 & 0 & q_{42} & 0 & 0\\ q_{31} & q_{32} & q_{33} & 0 & 0 & 0\end{bmatrix} \begin{Bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ \gamma_{yz}\\ \gamma_{xz}\\ \gamma_{xy}\end{Bmatrix} + \begin{bmatrix}d_{11} & 0 & 0\\ 0 & d_{22} & 0\\ 0 & 0 & d_{33}\end{bmatrix} \begin{Bmatrix}E_x\\ E_y\\ E_z\end{Bmatrix} + \begin{bmatrix}\mu_{11} & 0 & 0\\ 0 & \mu_{22} & 0\\ 0 & 0 & \mu_{33}\end{bmatrix} \begin{Bmatrix}H_x\\ H_y\\ H_z\end{Bmatrix} \quad (8)$$

where C_{ij}, e_{ij}, η_{ij}, d_{ij}, q_{ij}, μ_{ij} are elastic, piezoelectric, dielectric, magnetoelectric, piezomagnetic and magnetic coefficients. The multifield lading is considered as (Arshid *et al*. 2022):

$$\begin{aligned}\psi &= -\psi(x,y,t)\cos\left(\frac{\pi z}{h}\right) + \frac{2z}{h}\psi_0,\\ \phi &= -\phi(x,y,t)\cos\left(\frac{\pi z}{h}\right) + \frac{2z}{h}\phi_0\end{aligned} \quad (9)$$

Electric and magnetic fields are obtained as:

$$\begin{aligned}E_x &= -\frac{\partial\psi}{\partial x} = \frac{\partial\psi(x,y,t)}{\partial x}\cos\left(\frac{\pi z}{h}\right),\\ H_x &= -\frac{\partial\phi}{\partial x} = \frac{\partial\phi(x,y,t)}{\partial x}\cos\left(\frac{\pi z}{h}\right),\\ E_y &= -\frac{\partial\psi}{\partial y} = \frac{\partial\psi(x,y,t)}{\partial y}\cos\left(\frac{\pi z}{h}\right),\\ H_y &= -\frac{\partial\phi}{\partial y} = \frac{\partial\phi(x,y,t)}{\partial y}\cos\left(\frac{\pi z}{h}\right),\\ E_z &= -\frac{\partial\psi}{\partial z} = -\psi(x,y,t)\left(\frac{\pi}{h}\right)\sin\left(\frac{\pi z}{h}\right) - \frac{2z}{h}\psi_0,\\ H_z &= -\frac{\partial\phi}{\partial z} = -\phi(x,y,t)\left(\frac{\pi}{h}\right)\sin\left(\frac{\pi z}{h}\right) - \frac{2z}{h}\phi_0,\end{aligned} \quad (10)$$

Strain energy variation of a micro structure is expressed as (Sidhoum *et al*. 2018, Guenaneche *et al*. 2019, Foroutan *et al*. 2019, Draiche *et al*. 2021, Elsamak and Fayed 2021, Bouafia *et al*. 2017):

$$\delta U = \int_x \int_y \int_z [\sigma_{ij}\delta\varepsilon_{ij} + \tau_{ij}\delta\gamma_{ij} - D_i\delta E_i - B_i\delta H_i + \Sigma_{ij}\delta\beth_{ij}]\, dV \quad (11)$$

In which $\Sigma_{ij}, \beth_{ij}$ are couple stress tensor and symmetric curvature tensor with relation $\Sigma_{ij} = 2G\beth_{ij}$. $\beth_{ij}$ are components of the symmetric curvature tensor $\beth = \frac{1}{2}\left\{\overrightarrow{\nabla\theta} + \left(\overrightarrow{\nabla\theta}\right)^T\right\}$ in which $\theta = 1/2\, curl\vec{u}$ and $curl\vec{u}$ is computed as:

$$curl\vec{u} = \left(\frac{\partial w_b}{\partial y}+\frac{\partial w_s}{\partial y}+g(z)\frac{\partial \chi}{\partial y}+\frac{\partial w_b}{\partial y}+f'(z)\frac{\partial w_s}{\partial y}\right)\overrightarrow{e_x} + \left(-\frac{\partial w_b}{\partial x}-f'(z)\frac{\partial w_s}{\partial x}-\frac{\partial w_b}{\partial x}-\frac{\partial w_s}{\partial x}-g(z)\frac{\partial \chi}{\partial x}\right)\overrightarrow{e_y} + \begin{pmatrix} \frac{\partial v_0}{\partial x}-z\frac{\partial^2 w_b}{\partial x\partial y}-f(z)\frac{\partial^2 w_s}{\partial x\partial y} \\ -\frac{\partial u_0}{\partial y}+z\frac{\partial^2 w_b}{\partial x\partial y}+f(z)\frac{\partial^2 w_s}{\partial x\partial y} \end{pmatrix}\overrightarrow{e_z} \quad (12)$$

After calculation of $\overrightarrow{\nabla\theta}$, we will have:

$$\Sigma_{11} = G\Im^2\left(2\frac{\partial^2 w_b}{\partial x\partial y}+\left(1+f'(z)\right)\frac{\partial^2 w_s}{\partial x\partial y}+g(z)\frac{\partial^2 \chi}{\partial x\partial y}\right)$$
$$\Sigma_{22} = G\Im^2\left(-2\frac{\partial^2 w_b}{\partial x\partial y}-\left(1+f'(z)\right)\frac{\partial^2 w_s}{\partial x\partial y}-g(z)\frac{\partial^2 \chi}{\partial x\partial y}\right)$$
$$\Sigma_{12} = \frac{1}{2}G\Im^2\begin{pmatrix} 2\frac{\partial^2 w_b}{\partial y^2}+\left(1+f'(z)\right)\frac{\partial^2 w_s}{\partial y^2} \\ +g(z)\frac{\partial^2 \chi}{\partial y^2}-2\frac{\partial^2 w_b}{\partial x^2} \\ -\left(1+f'(z)\right)\frac{\partial^2 w_s}{\partial x^2}-g(z)\frac{\partial^2 \chi}{\partial x^2} \end{pmatrix} \quad (13)$$
$$\Sigma_{13} = \frac{1}{2}G\Im^2\left(f''(z)\frac{\partial w_s}{\partial y}+g'(z)\frac{\partial \chi}{\partial y}+\frac{\partial^2 v_0}{\partial x^2}-\frac{\partial^2 u_0}{\partial x\partial y}\right)$$
$$\Sigma_{23} = \frac{1}{2}G\Im^2\left(-f''(z)\frac{\partial w_s}{\partial y}-g'(z)\frac{\partial \chi}{\partial y}+\frac{\partial^2 v_0}{\partial x\partial y}-\frac{\partial^2 u_0}{\partial y^2}\right)$$

The external work is defined as:

$$\delta W_{Ext} = -\int_y\int_x \begin{bmatrix} \left(N_{0x}^{Mech}+N_{0x}^{Elec}+N_{0x}^{Mag}\right)\frac{\partial^2 w}{\partial x^2} \\ +\left(N_{0y}^{Mech}+N_{0y}^{Elec}+N_{0y}^{Mag}\right)\frac{\partial^2 w}{\partial y^2}-q \end{bmatrix}\delta w dxdy \quad (14)$$

Using the Hamilton's principle $\delta W+\delta T-\delta U$ the governing equations are derived as:

$$\delta u_0: -\frac{\partial N_{xx}}{\partial x}-\frac{\partial N_{xy}}{\partial y}-\frac{\partial^2 \Gamma_{13}}{\partial x\partial y}-\frac{\partial^2 \Gamma_{23}}{\partial y^2}=0$$
$$\delta v_0: -\frac{\partial N_{yy}}{\partial y}-\frac{\partial N_{xy}}{\partial x}+\frac{\partial^2 \Gamma_{13}}{\partial x^2}+\frac{\partial^2 \Gamma_{23}}{\partial x\partial y}=0$$
$$\delta w_b: -\frac{\partial^2 M_{xx}}{\partial x^2}-\frac{\partial^2 M_{yy}}{\partial y^2}-2\frac{\partial^2 M_{xy}}{\partial x\partial y}-2\frac{\partial^2 \Gamma_{22}}{\partial x\partial y}+2\frac{\partial^2 \Gamma_{11}}{\partial x\partial y} +2\frac{\partial^2 \Gamma_{12}}{\partial y^2}-2\frac{\partial^2 \Gamma_{12}}{\partial x^2}+\left(N_{0x}^{Mech}+N_{0x}^{Elec}+N_{0x}^{Mag}\right)\frac{\partial^2 w}{\partial x^2} +\left(N_{0y}^{Mech}+N_{0y}^{Elec}+N_{0y}^{Mag}\right)\frac{\partial^2 w}{\partial y^2}=\mathrm{q}$$
$$\delta w_s: -\frac{\partial^2 S_{xx}}{\partial x^2}-\frac{\partial^2 S_{yy}}{\partial y^2}-2\frac{\partial^2 S_{xy}}{\partial x\partial y}-\frac{\partial S_{xz}}{\partial x}-\frac{\partial S_{yz}}{\partial y} +\frac{\partial^2 \Lambda_{12}}{\partial y^2}-\frac{\partial^2 \Lambda_{12}}{\partial x^2}-\frac{\partial \Pi_{13}}{\partial y}+\frac{\partial \Pi_{23}}{\partial y}+\frac{\partial^2 \Lambda_{11}}{\partial x\partial y}-\frac{\partial^2 \Lambda_{22}}{\partial x\partial y} +\left(N_{0x}^{Mech}+N_{0x}^{Elec}+N_{0x}^{Mag}\right)\frac{\partial^2 w}{\partial x^2} +\left(N_{0y}^{Mech}+N_{0y}^{Elec}+N_{0y}^{Mag}\right)\frac{\partial^2 w}{\partial y^2}=\mathrm{q} \quad (15)$$
$$\delta \chi: -\frac{\partial S_{xz}}{\partial x}+S_{zz}-\frac{\partial S_{yz}}{\partial y}+\frac{\partial^2 \Xi_{11}}{\partial x\partial y}-\frac{\partial^2 \Xi_{22}}{\partial x\partial y} +\frac{\partial^2 \Xi_{12}}{\partial y^2}-\frac{\partial^2 \Xi_{12}}{\partial x^2}-\frac{\partial \Upsilon_{13}}{\partial y}+\frac{\partial \Upsilon_{23}}{\partial y} +\left(N_{0x}^{Mech}+N_{0x}^{Elec}+N_{0x}^{Mag}\right)\frac{\partial^2 w}{\partial x^2} +\left(N_{0y}^{Mech}+N_{0y}^{Elec}+N_{0y}^{Mag}\right)\frac{\partial^2 w}{\partial y^2}=0$$
$$\delta\psi: \frac{\partial \overline{D_x}}{\partial x}+\frac{\partial \overline{D_y}}{\partial y}+D_z=0$$
$$\delta\varphi: \frac{\partial \overline{B_x}}{\partial x}+\frac{\partial \overline{B_y}}{\partial y}+B_z=0$$

3. Numerical solution, results and discussion

The solution based on trigonometric functions is assumed as (Sidhoum *et al*. 2018, Guenaneche *et al*. 2019, Foroutan *et al*. 2019, Draiche *et al*. 2021, Elsamak and Fayed 2021, Bouafia *et al*. 2017, Arefi and Rahimi 2010, 2011, 2012a, b, c, 2014, Rahimi *et al*. 2011, 2012, Khoshgoftar *et al*. 2013, Arefi *et al*. 2011, 2018, 2019, 2020, Arefi and Zenkour 2016, 2017a, b, 2018, 2019, Arefi and Nahas 2014, Arefi 2013, 2014, Bidgoli and Arefi 2021, Arefi and Civalek 2020, Kholdi *et al*. 2022, Heidari *et al*. 2021, Arefi and Adab 2021, Adab and Arefi 2022, Adab *et al*. 2022.):

$$\begin{Bmatrix} u_0 \\ v_0 \\ (w_b, w_s, \chi) \\ (\psi, \phi) \end{Bmatrix} = \sum_n\sum_m \begin{Bmatrix} Ucos(\lambda_m x)\sin(\mu_n y) \\ Vsin(\lambda_m x)\cos(\mu_n y) \\ (W_b, W_s, \mathrm{X})sin(\lambda_m x)sin(\mu_n y) \\ (\Psi, \Phi)sin(\lambda_m x)sin(\mu_n y) \end{Bmatrix} \quad (16)$$

in which $\lambda_m = \frac{m\pi}{L_1}, \mu_n = \frac{n\pi}{L_2}$.

Multi-field critical load and free vibration analyses of the sandwich piezoelectric/piezomagnetic plates are studied in this section terms of significant input parameters of the plate. The results are presented in terms of geometric parameters and multi-filed loadings.

Listed in Table 1 is fundamental natural frequencies of a plate in terms of length to thickness ratio L/h based on various sources (Liew *et al*. 1993, Alibeigloo 2011, Bessaim *et al*. 2015, Abualnour *et al*. 2018) and various theories. An excellent agreement between the present results and corresponding results of previous papers is observed.

Shown in Table 2 is changes of fundamental frequencies of sandwich piezoelectric/piezomagnetic microplate with changes of micro scale parameter $\overline{\Im}$ for different face sheet to core thickness ratios $\mathrm{h}_p/\mathrm{h}_e$.

Table 1 comparative results of literature (Liew *et al*. 1993, Alibeigloo 2011, Bessaim *et al*. 2015, Abualnour *et al*. 2018)

L/h	Liew *et al*. (1993)	Alibeigloo *et al*. (2011)	Bessaim *et al*. (2015)	Abualnour *et al*. (2018)	Present
5/2	1.0954	1.0940	1.0996	1.0996	1.0999
10/3	1.2088	1.2075	1.2122	1.2122	1.2126
5	1.3209	1.3200	1.3237	1.3237	1.3240
10	1.4096	1.4096	1.4120	1.4120	1.4125
100	1.4440	1.4440	1.4460	1.4460	1.4466

Table 2 Changes of frequencies with changes of $\overline{\mathfrak{I}}$ for different h_p/h_e

$\overline{\mathfrak{I}}$	hp/he=0.02	hp/he=0.03	hp/he=0.04	hp/he=0.05
0	35212951	35135892	35060592	34987026
0.2	35224872	35147828	35072541	34998988
0.4	35260612	35183609	35108362	35034849
0.6	35320096	35243161	35167981	35094534
0.8	35403200	35326360	35251273	35177917
1	35509753	35433034	35358066	35284826

Table 3 Changes of frequencies with changes of $\mathfrak{I}$ for different h_p/h_e

$\overline{\mathfrak{I}}$	L/h=11.363	L/h=13.636	L/h=15.909	L/h=18.182
0	56340721	46950601	40243372	35060592
0.2	56389539	46978856	40261167	35072541
0.4	56535731	47063515	40314502	35108362
0.6	56778522	47204267	40403233	35167981
0.8	57116641	47400594	40527119	35251273
1	57548350	47651789	40685830	35358066

Table 4 Changes of critical applied electric potential $\psi_0)_{cr}$ in terms of $\overline{\mathfrak{I}}$ for different N_{0x}

hp/he	Nx0=0	Nx0=1e6	Nx0=2e6	Nx0=3e6	Nx0=4e6
0.02	42931.61	41986.59	41994.55	42002.51	42010.47
0.05	57679.38	57076.62	57081.05	57085.48	57089.91
0.1	71211.48	70900.42	70903.41	70906.4	70909.39
0.15	79562.84	79565.28	79567.72	79570.15	79572.59
0.2	86511.39	86513	86515.16	86517.33	86519.49

Table 5 Changes of $\psi_0)_{cr}$ in terms of $\overline{\mathfrak{I}}$ for different N_{0x}

hp/he	Nx0=0	Nx0=5e5	Nx0=1e6	Nx0=2e6
0.02	8426.584	8426.812	8434.642	8435.877
0.05	11315.46	11315.54	11322.68	11323.19
0.1	13998.89	13998.71	13996.65	13997.71
0.15	15501.88	15503.61	15500.11	15499.83
0.2	17006.7	17005.67	17008.37	17008.8

5. Conclusions

Free vibration and critical multi field analysis of a sandwich piezoelectric/piezomagnetic microplate was studied in this paper based on a higher order shear deformable model accounting shear and normal deformation including thickness stretching. The natural frequency responses and the critical electromagnetic loads are obtained in terms of geometric parameters, micro length scale parameter and loading parameters. The important results of this work are summarized as:

• A significant increase in natural frequency is concluded with an increase in micro scale parameter $\overline{\mathfrak{I}}$ because of an increase in structural stiffness.

• An increase in fundamental natural frequencies is observed with an increase in spring K_W and shear K_G parameters of Pasternak's foundation because of an increase in structural stiffness of foundation.

• An increase in critical applied electric potential $\phi_0)_{cr}$ is observed with an increase in micro scale parameter $\overline{\mathfrak{I}}$ and initial mechanical load N_{0x}.

• A decrease in critical applied magnetic potential $\psi_0)_{cr}$ is observed with an increase in micro scale parameter $\overline{\mathfrak{I}}$ and a decrease in initial mechanical load N_{0x}.

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