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# Vibration suppression of composite plates using smart electrorheological dampers

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ABSTRACT

The objective of the present study is to enlighten the influence of external electrorheological (ER) dampers on the dynamic behavior of composite laminated plates. Short time response along with electric field depended rheological behavior of ER fluids make these materials attractive for active vibration control of structures. To demonstrate the effect of ER damper on dynamic response of the composite plate, the finite element formulation based on the first order shear deformation theory (FSDT) is obtained for laminated plates. Moreover, the Bingham plastic model, which presents the post-yield behavior of the ER material, is used to model the ER fluid. Several numerical results are presented and effects of imperative parameters are discussed. It is shown that parameters such as applied voltage, controlled electric field, radius and initial gap of the electrodes, position of the ER damper and the stacking sequences of the composite plate have considerable effect on the vibration suppression time of the plate.

## 1. Introduction

Due to their superior mechanical properties such as high specific stiffness and strength, composite laminated structures have been widely utilized in civil, aerospace and other engineering fields. Applying such structures in many engineering applications has led to extensive research in dynamic analyses of the laminated composite structures. Therefore, the passive and active vibration control of these structures has attracted much attention in the last two decades.

Researchers have tried to find methods for vibration control of the structures which have higher efficiency and short time response. Utilizing smart dampers such as electrorheological or magnetorheological fluid damper/layer is one of these methods. Electrorheological (ER) and magnetorheological (MR) fluids are a class of smart materials which have controllable rheological properties and can be used for active vibration control of the structures. The ER fluids which are suspensions of dielectric particles in non-polar liquids form chain-like structures when exposed to an electric field. Numerous studies have been conducted to investigate the mechanical and damping characteristics of ER or MR fluids. The ER fluid based structures have been used by Kim et al. [1] to control and suppress the vibration of a structure. Brennan et al. [2] analytically and experimentally compared the behavior of ER dampers operating in shear and valve modes. Stanway et al. [3] presented a comprehensive survey on the modeling and control of different modes of operation of ER fluid-based devices used for vibration control. Design, construction and testing of an ER damper have been implemented by Makris et al. [4] for vibration and seismic protection of civil structures. Dyke et al. [5] conducted experiments to investigate the effect of optimally controlled MR dampers to reduce the seismic response of a three-story test structure. Park et al. [6] investigated the material characteristics of an ER fluid subjected to an electric field and temperature. The dynamic properties of an ER fluid under shear and flow modes were studied by Lee and Choi [7]. Liao and Lai [8] investigated the effect of different parameters on vibration control of an MR damper subjected to harmonic excitation. El Wahed et al. [9] presented an approach for analyzing the behavior of squeeze-flow mode ER fluids. In this approach, the yield stress is determined iteratively by minimizing the difference between observed and predicted values of the transmitted force. See [10] presented a review on the advancement in modeling and application of the ER fluids. He investigated the characteristics of different types of ER materials and different methods (experimental, analytical or simulation) which have been used by other researchers for modeling the ER fluids. Jung et al. [11] used a squeeze mode ER support to control the vibration of a flexible beam. They applied a proportional integral derivative (PID) controller to illustrate the damping force controllability of the ER mount. Sapiński [12] experimentally investigated the shock isolation performance of an MR damper used as a suspension of a driver's seat.

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## Nomenclature

| | |
|---|---|
| $a$, $b$ | dimensions of the plate in $x$ and $y$ directions |
| $h$ | plate thickness |
| $h_0$ | initial gap between the electrodes |
| $l_u$, $l_v$ and $l_w$ | projections of $L_D$ in $x$, $y$ and $z$ directions |
| $l'_u$, $l'_v$ and $l'_w$ | projections of $L'_D$ in $x$, $y$ and $z$ directions |
| $m$ | number of sub-laminate stacking sequences |
| $n$ | number of orthotropic layers in ply-level configuration |
| $q_u$, $q_v$ and $q_w$ | instant displacements of the attach point of the damper to the composite plate in $u$, $v$ and $w$ directions |
| $t$ | time |
| $u$, $v$ and $w$ | displacements in the $x$, $y$ and $z$ directions |
| $u_0$, $v_0$ and $w_0$ | mid-plane displacement components |
| $A_{ij}$, $B_{ij}$, $D_{ij}$ | stretching stiffness, bending- stretching coupling stiffness and bending stiffness |
| $[C]$ | damping matrix |
| $C_u^{ER}$, $C_v^{ER}$ and $C_w^{ER}$ | viscous damping components in $u$, $v$ and $w$ directions |
| $[D^{ER}]$ | relative equivalent electric dependent Coulomb damping matrix |
| $D_u^{ER}$, $D_v^{ER}$ and $D_w^{ER}$ | Coulomb damping components in $u$, $v$ and $w$ directions |
| $E_1$, $E_2$ | longitudinal and transverse Young's moduli |
| $E$ | electric field |
| $F_d(t)$ | total damping force |
| $G_{12}$, $G_{23}$, $G_{13}$ | shear moduli for orthotropic materials with reference to principle axes |
| $H_{ij}$ | transverse shear stiffness |
| $[K]$ | global stiffness matrix |
| $L_D$ | Length of ER damper before deformation of the plate |
| $L'_D$ | instantaneous length of the ER damper |
| $L_P$ | horizontal projection of $L'_D$ |
| $[M]$ | global mass matrix |
| $\tilde{M}$ | moment resultants |
| $\tilde{N}$ | membrane force resultants |
| $\tilde{Q}$ | transverse shear force |
| $\alpha$ and $\beta$ | inherent properties of ER fluid |
| $\delta_{Damper}(t)$ | instantaneous gap between the damper electrodes |
| $\dot{\delta}_{Damper}(t)$ | relative velocity of the two electrodes |
| $\tilde{\varepsilon}^0$ | mid-plane strains vector |
| $\eta$ | Newtonian viscosity |
| $\phi_x$ and $\phi_y$ | rotations |
| $\varphi$ | Azimuth angle at $t=0$ |
| $\psi$ | elevation angle at $t=0$ |
| $\tilde{\kappa}$ | curvature vector |
| $\rho$ | density |
| $\theta$ | fiber angle |
| $\tau_E$ | filed dependent shear stress |
| $\tau_{NE}$ | field independent shear stress |
| $\varphi'$ and $\psi'$ | instantaneous angles of the ER damper |
| $\tilde{\gamma}$ | shear strains |
| $\dot{\gamma}$ | shear rate |
| $\nu_{12}$ | Poisson's ratio |

The Bingham plastic model of ER fluid has been used by Pahlavan and Rezaeepazhand [13] to investigate the damping treatment of beam-like structures with an external ER damper. Yeh [14] used the viscoelastic Kelvin model of ER fluid to study the free vibration and damping characteristics of the cylindrical sandwich shell with an intermediate ER layer. Design and testing of an MR damper for high-mobility multi-purpose wheeled vehicle (HMMWV) have been developed by Dogruer et al. [15]. The dynamic behavior of a shear mode ER damper has been studied by Nguyen and Choi [16] based on the Bingham model of the ER fluid. Design, build and testing of a radial flow mode MR damper have been implemented by Aydar et al. [17]. Mohammadi and Sedaghati [18] investigated the nonlinear vibration behavior of sandwich shell structures with a constrained ER fluid. In his recent work, Yeh [19] presented the vibration of the sandwich plate with MR elastomer damping treatment. The finite element method is used to model the sandwich plate with MR elastomer core.

Although there are numerous studies that have been devoted to vibration and dynamic characteristics of smart structures, to the best of the authors' knowledge little attempt has been made to investigate the effect of various parameters on the dynamic behavior of the laminated composite plate with smart external dampers.

In the present study, the dynamic behavior of the laminated composite plate with an external ER damper is investigated using the finite element method. Nine nodes quadratic rectangular element and first order shear deformation theory are used for obtaining the mass and stiffness matrices of the composite plate. The Bingham plastic model is used to model the behavior of the ER fluid. From three different modes of ER fluids operation (flow mode, shear mode and squeeze mode), the squeeze mode is considered in this study. To produce constant levels of electric field a simple closed loop control system is employed which considerably enhances the damping behavior of the structure.

## 2. Problem formulation and solution method

### 2.1. Model of the ER fluid

As previously mentioned, the material properties of ER fluids are sensitive to a strong electric field. In other words, the yield stress and viscosity of the ER fluid will dramatically alter in the presence of electric field. Based on the Bingham model, the shear stress in ER fluids consists of two parts – the field independent shear stress ($\tau_{NE}$) and field dependent part ($\tau_E$) [13]:

$$\tau(E) = \tau_{NE} + \tau_E \tag{1}$$

where, $\tau_{NE} = \eta\dot{\gamma}$ is the field independent shear stress defined in terms of shear rate ($\dot{\gamma}$) and the Newtonian viscosity ($\eta$). The electric field ($E$) controlled yield stress ($\tau_E$) of the Bingham model is defined as $\tau_E = \alpha E^{\beta}$ [11]. $\alpha$ and $\beta$ are constants which depend on the inherent properties of ER fluid and determined experimentally. These parameters for particle-type ER fluid used in this study, as reported by Jung et al. [11], are equal $\alpha = 427$, $\beta = 1.2$, and $\eta = 30\ cSt$ at room temperature.

### 2.2. Mathematical model of external ER damper

In the present study, the squeeze mode of the ER damper is considered. According to the operation of this mode, the lower electrode is fixed to the base plate, while the upper electrode is free to move up and down along the damper direction. The schematic representation of the laminated composite plate with an external ER damper is illustrated in Fig. 1(a). In Fig. 1(b), $L_D$ is the length of the ER damper before deformation of the plate. The azimuth $\varphi$ and elevation $\psi$ are the initial (at $t=0$) angles of the ER damper in radians measured from the positive $x$ axis and the $xy$ plane, respectively. Furthermore, $l_u$, $l_v$ and $l_w$ are the projections of $L_D$ in $x$, $y$ and $z$ directions, respectively. $L'_D$ is the instantaneous