Chapter 2
Literature Review

The vibration analysis of laminated composite controllable fluid (ER and MR fluids) sandwich plate consists of many technical challenges including the development of constitutive equations of composite laminate, MR fluid characterization, fabrication of composite laminate and sandwich plate, identification localized partial treatment and optimization of location of MR pockets, etc. The reported studies are thoroughly reviewed in various aspects including analytical and experimental methods to understand the background research and discussed and grouped under relevant topics in the following subsections.

2.1. MULTI-LAYERED LAMINATED COMPOSITES

Multi layered composite plate has been used in aircraft and aerospace engineering applications for more than 40 years due to their high bending stiffness and strength to small weight ratios, long fatigue life and resistance to electrochemical corrosion. Further, the laminated composite structures are increasingly being used in marine, transport and civil construction applications due to their high strength to weight ratio, high bending strength, cost effectiveness, durability and low maintenance cost. It is necessary to develop the reliable and practical models to predict the static and dynamic behavior of the structure. There are extensive amount of research works are available in the field of vibration analysis on multilayered composite plate. Both analytical and numerical methods were used to derive the governing equation of motion of the structures. The finite element methods have been used in the vibration analysis of complex composite structures (Kim et al, (1990); Niyogi et al, (1999); Pandit et al,(2007) and Rikards et al, (1995)). FEM was used to analyze the laminated composite plates in terms static (Shankara et al (1996), dynamic (Latheswary et al, (2004)), buckling (Hasan et al, (2003); Leissa,(1992); Noor, (1995); Sundaresan et al, (1996)) and geometric nonlinearity (Ganapathi et al., (1996); Zhang and Kim, (2006)); conditions based on various lamination theories such as classical lamination theory (Robbins et al, (2010), first order shear deformation theory (Ribeiro,(2005)) , higher order shear deformation theory (Matsunaga,(2000), layer wise lamination theory and continuum-based 3D elasticity...

2.2. CONTROLLABLE MR FLUIDS

Semi-active control devices that possess the advantages of active and passive control devices have been proposed for structural control applications (Carlson, 1994; See, 2004). These devices include controllable fluids such as electro-rheological (ER) and magneto-rheological (MR) fluids. Such fluids exhibit rapid change in their rheological properties and thus in the damping and stiffness properties with application of an electric or magnetic field. Generally the active control systems requires a significant amount of energy into the system while the semi-active control devices involve modifications of mechanical properties of the system in the preferred manner with only modest exterior energy (Dogruer et al., 2008). Consequently, extensive numbers of research works have done on the semi active devices development including ER and MR fluid applications. The property of interest for the controllable ER and MR fluids is that they demonstrate an electric or magnetic field-dependent yield stress which is associated with the formation of chains of polarizable particles in the direction of the parallel to applied electric or magnetic field (Fig. 1.1). The formations of chains yields force of attraction among the particles due to the applied magnetic field and consequently, manifest the resistance to shear deformation in the fluid. The yield force and viscosity of controllable fluids can be continuously increase or decrease under the application of varying electric or magnetic fields.

Choi et al., (2005) studied the flow behavior of ER/MR fluid theoretically and experimentally. The flow behavior equations (shear stress Vs torque and shear rate Vs angular velocity) were developed on the basis of the Bingham plastic, bi-viscous and Herscho- Bulkley constitutive models. Ashour et al., (1996) developed the new MR fluid using the modern improved manufacturing process at low cost to demonstrate the engineering feasibility. Laboratory experiment was conducted to optimize the quality and properties of MR fluids and HAAKE cone-plate viscometer was utilized to measure the properties of MR fluids. Compared to other conventional devices, MR
fluids based devices provide the faster responses, improved performance, simplicity of design and reduced cost.

The MR fluid chains formation was simulated under various magnetic field and the particle motions was determined by the magnetic interaction, contact interaction and viscous force. Simulated results were compared with the experimental results (Li et al., 2005). Carlson (2002) investigated the durability, life and working conditions of MR fluid apart from the yield strength in order to improve or increase the commercial success. Compared to the ER fluids, MR fluids are known to exhibit considerably higher dynamic yield strength and greater insensitivity to temperature variation and contaminants (Weiss et al., 1994; Wang and Meng, 2001). The yield stress of the MR fluid lies in the order of 2 – 3 kPa in the absence of a magnetic field and it rapidly exceeds 80 kPa under the application of a magnetic field in the order of 3000 Oe (Carlson and Weiss, 1994). With application of varying magnetic field, these fluids are considered to yield high bandwidth control through rapid variations in the rheological properties. Kim et al., (2005) experimentally investigated the material characterization of MR fluid at high frequency ranges application. The storage modulus and loss modulus were measured based on the wave transmission at the frequency ranges of 50-100 kHz. The Storage modulus and loss modulus were calculated in two different positions (orthogonal and parallel) of applied magnetic field. The study was concluded that orthogonal position of applied magnetic field has the effective method to control the MR fluid behavior.

The utilization of MR fluids have been increasing in the various semi-active damping control applications in the low to moderate frequency ranges, including automotive suspension (Han et al., 2006), structures (Oh and Onoda, 2002; Pranoto et al., 2002; Yao et al., 2002;), telerobotic systems (Farzad, 2008), fluid clutches (Lee et al. 2000), optical polishing (Kordonski and Golini, 1999) and a variety of aerospace (Choi and Wereley, 2003; Hu and Wereley, 2008; Kamath et al., 1999; Marathe et al., 1998; Wereley et al., 1999; Zhao et al., 2004;), vibration isolation systems (Choi et al., 2005;Hiemenz et al., 2008;Stelzer et al., 2003;Yoshoka et al., 2002;), civil (Ribakov and Gluck, 2002; Sodeyamma et al., 2001), valves (Yoo and Wereley, 2002) and automotive (Breese, D.G. and Gordanejad, F., 2003;Lam and Liao, 2003; Linder et al., 2003,) damping applications.
Figure 2.1. Configurations of particles suspended in ER/MR fluid: (a) in the absence of electric or magnetic field applied; (b) under electric or magnetic field; and (c) formation of particle chain structure under applied field.

### 2.3. MODES OF OPERATION OF MR FLUIDS

MR fluid could be used to control the vibration of structures. It has three primary modes, namely the flow mode, the shear mode and the squeeze-flow mode as shown Figure 1.2 (Wang and Meng, 2001; Wereley and Pang, 1998). In the flow mode, fluid is flowing due to the pressure drop between two stationary plates and proper magnetic field is applied in a direction of perpendicular to the plane of the plates in order to control the flow resistance. It can be used the servo-valves, shock absorbers (Wang and Li, 2006; Ericksen and Gordaninejad, 2003; Nguyen and Choi, 2009), dampers (Xu et al., 2000; Yao et al., 2000) and actuators. In the shear mode, fluid between two plates moving relative to one another and magnetic field is applied perpendicular to the motion of the shear forces. It includes clutches, brakes (Jansen and Dyke, 2000; Li and Du, 2003), locking devices and structural composites. In the squeeze mode, fluid between two plates moving in a direction perpendicular to the plane of the plates and the magnetic field is applied in a direction perpendicular to the plane of the plates, so as to restrict fluid flow in the direction parallel to the plates. Squeeze-flow mode is particularly suitable for applications involving the control of very low magnitude movements, in the order of millimeters, but large dynamic forces (Mazland et al. 2007; See, 2003; Wang et al., 2005).
2.4. MODELING OF MR FLUIDS

Many experimental tests have been carried out by many researchers to measure the mechanical properties of magnetorheological (MR) fluids such as storage modulus, loss modulus, shear stress and shear strain. (Jolly et al., 1998; Genç and Phule; 2002; Weiss et al., 1994). The shear modulus of the MR fluid has been described in a number of studies on the basis of measured shear stress-shear strain properties (Weiss et al., 1994; Choi et al., 1995; Li et al., 1999; Wang and Kamath, 2006). The shear stress and shear strain properties of the MR fluid have been characterized into two distinguished regions, referred to as pre-yield and post-yield regions, as shown in Figure 1.3. Although the shear stress-strain properties of the MR material strongly depend upon the applied magnetic field, the measured properties generally exhibit quite comparable patterns. In the pre-yield regime, the MR material exhibit viscoelastic behavior and derived by the complex modulus $G^*$ as (Li et al., 1999; Li et al., 2002):

$$G^* = G' + iG''$$  \hspace{1cm} (1)

where $G'$ is the storage modulus of the MR fluid, which is defined as the average energy stored per unit volume of the material during a deformation cycle, and $G''$ is the loss modulus which is proportional to the average energy dissipated per unit volume of MR material over a loading and unloading cycle. Therefore shear stress can be expressed as,

$$\tau = G^* \gamma$$  \hspace{1cm} (2)

where $\gamma$ is the shear strain (Jolly et al., 1998).
In the post-yield regime shear stress is above the yield stress and is the dominant mode of operation in most devices such as dampers, valves, and clutches. When the fluid undergoes a shear thinning or thickening, its post-yield behavior is non-linear and this effect requires a fluid model to account for the non-Newtonian behavior of MR fluids. The post-yield behavior of the MR materials has been approximately characterized by three models in terms of shear stress and torque as well as shear rate and angular velocity, namely, the Bingham plastic model, the Herschel-Bulkley model and the bi-viscous model (Choi et al., 2001). According to Bingham and Herschel-Bulkley models, the MR fluid behaves as a Newtonian fluid in the absence of the magnetic field. The fluid, however, is characterized by a non-Newtonian fluid, when exposed to a magnetic field. Mathematically, these models are characterized by yield stresses as:

**Bingham plastic model:**

\[
\tau = \begin{cases} 
\tau_y + \eta \dot{\gamma} ; & \tau > \tau_y \\
0 ; & \tau \leq \tau_y 
\end{cases}
\]

**Herschel-Bulkley model:**

\[
\tau = \begin{cases} 
\left(\tau_y + K|\dot{\gamma}|^{1/m}\right)\text{sgn}(\dot{\gamma}) ; & \tau > \tau_y \\
0 ; & \tau \leq \tau_y 
\end{cases}
\]
Biviscous model:

\[ \tau = \begin{cases} 
\tau_{yd} + \eta_{po}\dot{\gamma}; & \tau > \tau_{ys} \\
\eta_{pr}\dot{\gamma}; & \tau \leq \tau_{ys} 
\end{cases} \]  

(3)

where \( \tau \) is the shear stress, \( \tau_y \) is the yield stress, \( \eta \) is the plastic viscosity, \( \dot{\gamma} \) is the shear strain rate, \( m \) is the flow index and \( K \) is a consistency parameter. The constants \( \eta_{pr} \) and \( \eta_{po} \) are the viscosity in the pre-yield and post yield regions, respectively. For \( K= \eta \) and \( m=1 \), the Herschel-Bulkley model reduces to the Bingham plastic model.

The Bingham plastic model is often used to describe the post yield phenomenon (Choi et al., 1995; Li et al., 1999; Stanway et al., 1996, Weiss et al., 1994) of the MR fluid. In the Bingham plastic model, MR fluids are assumed to be Newtonian fluids in post-yield regime, with a constant plastic viscosity assumption. However, for cases where the fluid experiences post-yield shear thinning or shear thickening, the assumption of constant plastic viscosity may not be valid. Marksmieir et al. (1998) experimentally investigated the shear thinning effect of ER fluid on the ER grease damper. It was concluded that the Herschel-Bulkley model would be more appropriate than the Bingham plastic model for ER/MR fluids in the non-Newtonian post yield region.

Jolly et al. (1999) investigated the formulation of MR fluids for various applications. It was concluded that depends on the application, the properties MR fluids have been varying in the balanced manner. Genc et al., (2001) studied the yield stresses of MR fluids by varying the iron particle sizes. Two set of grades (grade A-coarser size and Grade B-smaller size) of MR fluids were prepared in silicone oil. The study suggested through SEM and XRD studies that smaller particle size iron powder yields lower yield stress compared coarser size. Li et al., (2005) simulated the chain formation process of ferromagnetic particles of MR fluid under the application of magnetic force, viscous force and repelling forces. The dynamics of particles were analyzed numerically and validated by experimental investigation. This developed simulation techniques was very useful to identify the overall behavior of MR fluids.

The stress-strain properties of MR-fluids were studied by Weiss et al., (1994) and Li et al., (1999) under various magnetic field intensities. Also laboratory
experiments were conducted to calculate the storage moduli and loss moduli of MR fluid with respect to the magnetic fields. A vast number of studies have been attempted to develop models for relating the stiffness and damping properties of the structures. (Koo et al., 2006; Li et al., 2002). Kim et al., (2014) investigated a visco-plastic flow behavior of MR fluid with field-dependent yield stress and wall slip boundary conditions. The magnetic field-dependent constitutive bi-viscosity model was used to analyse the Couette-Poiseuille flows of a viscoplastic MR fluid.

2.5. APPLICATION OF MR FLUIDS – MR DAMPERS

In order to increase the safety and reliability of any static and dynamic systems, the vibration control strategies and developments in controllable actuators is important. Therefore the semi-active MR-fluid dampers are being increasingly used in vehicle suspension systems, machineries and structures. They can offer large range of damping force capacity with minimal power requirements to provide improved performances.

A semi-active vibration isolation system was developed by Margolis (1983) and compared with the passive and active vibration isolation systems. The study concluded that semi-active system provide very good performance which could be employed with the realistic feedback signals when controlling the vibration. The MR-fluid damper designed on the basis of Bingham model and the sky control to employ in the a semi-active suspension seat (Choi et al., 2000). The dynamic performances of a quarter car system incorporating MR fluid suspension damper were investigated experimentally by Goncalves (2001).The response characteristics of various semi-active control strategies including skyhook, ground hook, hybrid, displacement skyhook and relative displacement skyhook controls were compared based on the performance.

The performance of a MR damper integrated in a single-degree of-freedom (DOF) suspension system model was investigated by Lai and Liao (2002) subjected to a random excitation. The study proposed a control law based on sliding mode controller. Yang et al., (2002) studied features and performance of MR dampers for structural vibration reduction. These semi active control MR dampers are used in
number of real world applications because of simple design, lower power requirement and scalability. A quasi-static axi-symmetric model was used to design the MR damper and it was validated by simple parallel plate model and experimental results. These results showed that MR damper provides the large controllable damping. Dynamic response of the MR damper was also analyzed experimentally. It was also concluded that parallel coils damper provides faster response time than the series coil damper. Further the performance characteristics of the MR-fluid suspension using a H∞ controller for vibration suppression of a full vehicle system model comprising four independent MR damper suspensions were investigated by Choi et al. (2002). The feasibility of implementation of MR damper was investigated by Liao and Wang (2003) in order to improve the ride quality of railway vehicles using the LQG control law.

Pranoto et al., (2004) developed the shear type linear MR fluid damper for controlling the vibration of flexible structures or plates of aircraft wings. The performance of MR damper was evaluated theoretically and validated experimentally by conducting the test in vibration suppressions of the cantilever plate. The study concluded that MR damper provides many advantages compared to other systems and it satisfies all the conditions for plate vibration control.

Wang et al., (2005) developed the MR fluid based semi-active tuned liquid column damper for vibration reduction of building structures. It was concluded that MR-TLCD damping performance could be controlled by changing the applied magnetic field depends on loading conditions and structural uncertainty like wind induced displacement and acceleration. Both Bingham plasticity model and Bouc-Wen hysteresis model were used to develop the simplified inverse dynamics (SID) models for MR fluid dampers. The developed SID model was used to calculate the optimal fluid yield stress and optimal input current by Bingham plasticity model and Bouc-Wen hysteresis model respectively. Also the piston velocity feedback algorithm and damper force feedback algorithm were developed for both the model in order to improve the damping performance of MR damper.

A numerical investigation of a control strategy based on genetic algorithm with fuzzy controller developed by Yan and Zhou (2006) to minimize both the maximum displacement and acceleration response of the structure equipped with a
MR damper under earthquake like excitation. A new vibration suppression system was developed by Pranoto et al., (2007). It consists of two parts such as an electromagnetic actuator and MR fluid rotary shear damper. electromagnetic actuator provides vibration isolations by controlling and measuring the displacement of the base. MR fluid rotary shear damper provides the vibration suppression of the resonance peaks of the system. Experimental tests were conducted to validate the effectiveness of the system. Gu and Oyadiji, (2008) developed an adaptive neuro-fuzzy inference system (ANFIS) controller for reduction of vibration in multi-degree of freedom structure under earthquake conditions. A space truss type structure was used to test the damping performance of semi-active MR damper. Finite element methods were used to derive the stiffness and mass matrices of the MR damper. Experiments were conducted to validate the finite element simulation (Dominguez et al., 2008).

Spelta et al., (2009) developed the semi-active actuator to control the reduction of vibration and noise in the washing machine. Two adaptive algorithms were used to improve the damping characteristics MR damper. Cesmeci and Engin, (2010), the dynamic performance of a linear MR fluid Damper were investigated experimentally. The fabricated MR damper was tested on a conventional shock machine. The Bingham plastic constitutive model was used to study the flow analysis of MR dampers.

Ghiotti et al., (2010) developed the MR dampers to withstand the breakthrough shock generated in the metal working presses particularly blanking and piercing operations. Full-scale experiments model were used to understand the feasibility and the potential benefit of MR dampers over conventional dampers. A block-box model (BBM) is a simple direct modeling method which was designed for the identification of typical MR fluid damper. Simple self-tuning fuzzy techniques were used to design the MR dampers. The back propagation algorithm and gradient descent method were used to improve the accuracy of the proposed model. It was concluded that the behavior MR damper was well defined and suitable for the self-sensing damping force control systems.
The mechanical behavior of MR damper was described experimentally for analyzing the seismic control of longitudinal displacements of a suspension bridge under different earthquake conditions (Yang et al., 2011). MR dampers were optimized based on two objectives functions such as the target damper force as 1000 N and the maximum magnetic flux density. Finite element analysis were used to get the desired optimal values based on the geometrical magnitudes, current excitation and yield stress. MR damper was fabricated and tested based on the optimized parameters.

A simple non-linear hysteretic model was developed by Yang et al., (2013) for the analysis of MR damper to represent the hysteretic characteristic. The non-linear least square method with MATLAB software was used to identify the parameters of the model. It was concluded that the current model has higher accuracy than the Bingham model, the non-linear hysteretic bi-viscous model and the double-sigmoid model. The effectiveness of the MR damper was demonstrated for various engineering control applications under random excitations. Sternberg et al., (2014) studied the multi-physics behavior of a MR damper using finite element methods and validated by experimental measurements. Finite element model was used to measure the responses of the MR damper in the magneto static and fluid dynamic problems. Numerical results were validated by testing the fabricated large-capacity (97 tons) MR damper.

Weber, (2014) developed a semi-active vibration absorber based on the real time controlled MR damper for reduction of structural vibrations. The stiffness force and damping force are controlled by adjusting the natural frequency and minimizing internal damping of the MR-SVA to improve the performance of the system. The results showed that the MR-SVA has higher dynamic performance than the passive type dampers. The vibration reduction of MR-SVA has been improved between 12.4% and 60% depending on the level of excitation compared to passive methods.

The above literature reviews have concluded that MR fluid dampers can provide effective control of vibration in various applications such as vehicle suspension, machineries mountings, buildings and bridge structures. A wide range of controllers and control algorithms were used in the reported studies in order to
achieve the controlled damping force for realizing the objectives of the respective studies. The MR-dampers could be effectively applied in a semi-active control manner with only minimal external power. However, it is suitable for particular modes of operation. MR fluid damping treatment is required for high bandwidth control requirement. Fewer studies have been explored the applications of MR-fluids as controllable damping treatment for structures. These studies are described in the following subsections.

2.6. ER/MR FLUID BASED SANDWICH CONSTRUCTION IN VIBRATION REDUCTION

In the past few years, a structural sandwich system with integrated control capabilities is the key research area in engineering. It provides higher flexural stiffness to weight ratio, lower lateral deformations, higher buckling resistance and higher the natural frequencies. Therefore the researches have been focused to utilize the features of ER/MR fluids on the designs of ER/MR dampers in vibration suppression of structures (Aldemir, 2003; Dyke et al., 1998; Makris et al., 1996; Pranoto et al., 2004; Stanway et al., 1996; Zhang and Roschke, 1999) and systems (Choi, 1999, 2001 and 2002; Du et al., 2005; Hong et al., 2002; Peel et al., 1996; Yao et al., 2002). In structural applications, the ER/MR fluid dampers has been used in discrete locations (Pahlavan and Rezaee pazhand, 2007; J. Dyke et al., 1998; Pranoto et al., 2004; Bashtovoi et al., 2002) or the MR/ER fluid layer treatments has been used in selected structure in order to reduce the vibration of the structural members. The former approach may require multiple damping elements because the structures generally involved in multiple modes of vibration. So the design of multiple dampers in single structure may lead to higher weight and complexity in design. Alternatively, the distributed control force throughout the sandwich structures could be achieved by embedding ER/MR material layers between two layers. This approach can facilitate structure vibration control over a broad range of frequencies through variations in distributed stiffness and damping properties in response to applied electric or magnetic field.

The development of ER material based sandwich structures was initiated by Gandhi et al (1989). The dynamic characteristics of the ER fluid based sandwich
structures were investigated experimentally and concluded that the structure damping ratio and the natural frequencies could be increased with increase in electric field. It was shown that ER fluids have greater sensitivity in temperature variations. The effect of electric field on the rheological properties of ER fluid based sandwich structures were evaluated experimentally by Choi et al. (1990, 1992). Experiments were performed on various compositions of ER fluids including cornstarch-corn oil and Zeolite-silicone oil. Substantial variations in natural frequencies in all modes were observed with changes in the applied electric field and reduction in deflection at all the modes considered under forced vibration excitation.

The vibration characteristics of a cantilever beam locally linked with ER fluid layer were investigated experimentally by Haiqing et al. (1993). The study suggested that the locally applied ER fluid layer works as a complex spring. The stiffness and damping properties of the structure could be altered by controlling the applied electric field. Leng et al. (1995) experimentally investigated the vibration analysis of ER fluid composite sandwich beam. It was concluded that the first three modes of natural frequencies and damping factors were increased with increasing the applied electric field.

Yalcintas and Coulter (1995) developed an analytical model to characterize the forced vibration response of a simply supported ER sandwich beam using RKU (Ross-Kervin-Ungar) model. The numerical solutions were validated through experimental measurements. Also the authors extended their work to formulate the analytical model using Mead and Markus (1969) theory to investigate the dynamic characteristics of ER sandwich beam with various boundary conditions. The study showed that the effectiveness of dynamic properties of sandwich beam in terms of natural frequencies, loss factor and the mode shapes.

The vibration analysis of a fully and partially treated ER fluid sandwich beam was analyzed by Haiqing and King (1997) under clamped end conditions. The study concluded that the natural frequencies and loss factors of the sandwich beam depends on the length of ER fluid layer. Qiu and Khajika (1999) studied the vibration analysis of three-layered beams and five-layered beams with ER materials. It was concluded that the damping factor of a five-layer beam could be larger than that of a three-layer
beam. Lee and Jwo (2001) experimentally analyzed the effect of spacing of parallel grooves on the local distribution of an electric field. Significant variations were observed in the storage modulus, loss modulus and first two natural frequencies by providing finer spacing of the grooves in the electrodes.

Yeh and Chen (2004) evaluated the variation in the stiffness and natural frequency of the sandwich plate with ER fluid by varying the applied electric field. They concluded that the resonance frequencies of the sandwich plate could be increased with increase in electric field and decreased with increase in thickness of the ER layer. Furthermore the thickness of the constrained layer has a significant effect on the stability of the system. In-addition to the natural frequencies of the system the modal loss factor was analyzed for various electric fields.

The dynamic stability of a sandwich plate with an ER fluid core and constrained layer were discussed by Yeh and Chen (2005) using finite element method and Bolotin’s method. The stiffness of system is increased with increasing the magnitude of electric field and constraining layer thickness. The natural frequencies and the modal damping factors were evaluated at various electric fields and the instability regions were also identified. The vibration responses of an ER fluid based orthotropic sandwich plate were investigated by Yeh and Chen (2007) using Hamilton’s principle. The effects of the electric fields on the dynamic behavior of the orthotropic sandwich plate were studied. Two kinds of ER fluids were used to study the variation in the visco-elastic behavior of the system. It was concluded that the damping characteristics of the orthotropic sandwich system could be effectively controlled by the applied electric field.

Extensive research works have been done on the dynamic property evaluation of sandwich structures with ER fluid layers. However limited numbers of analysis are available on sandwich structures with MR fluid as the core layer. Yalcintas and Dai (1999, 2004) analyzed the dynamic responses of a MR fluid adaptive sandwich beam using the energy approach and compared the responses with the structure employing ER fluid. It was concluded that the natural frequencies of MR fluid based adaptive sandwich beam could be nearly twice of the ER fluid based sandwich beam.
Sun et al (2003) analytically studied the dynamic responses of a MR fluid sandwich beam using the energy approach and the results are validated by experimental measured data. Oscillatory rheometry techniques were used to carry out experiments to develop the relationship between the applied magnetic field and complex shear modulus of the MR fluid. Yeh and Shih (2006) studied theoretically the dynamic responses of MR material based adaptive beam under axial harmonic load using DiTaranto sandwich beam theory. Hu et al (2006) investigated the vibration characteristics of a magneto rheological fluid based sandwich beam using DiTaranto sixth order partial differential equation. It was shown that the natural frequencies and loss factors of the MRF beam were increased with increasing applied magnetic field strength.

Rajamohan et al (2010a) derived the governing differential equations of motion by FEM and Ritz formulations for a sandwich beam with MR-fluid treatment and validated through experiments conducted on a cantilever sandwich beam. Various parametric studies were performed in terms of variations of the natural frequencies and loss factor as functions of the applied magnetic field and thickness of the MR fluid layer for various boundary conditions.

Lara-Prieto et al (2010) experimentally investigated the controllability of vibration characteristics of magnetorheological cantilever sandwich beams under various magnetic field intensities. The effects of applied magnetic field at partial and full length of MR fluid sandwich beam were analyzed. Rajamohan et al (2010b) presented finite element formulations for a partially-treated MR fluid sandwich beam comprising various MR-fluid segments for different boundary conditions. The study concluded that the location and length of the MR fluid segments have significant effect on the natural frequencies and the loss factors in addition to the intensity of the magnetic field and the boundary conditions.

The influence of locations of the MR fluid segments on the modal damping factor was further investigated under different end conditions using modal strain energy approach and FEM by Rajamohan et al (2010c). The effectiveness of the linear quadratic regulator and flexible mode shape method based optimal control techniques on controlling transient and forced vibration responses of a fully and partially treated
MR fluid sandwich were investigated by Rajamohan et al (2011). The vibration response of a MR fluid sandwich plate was analyzed by Li et al (2011). It was shown that the natural frequencies increase with increase in applied magnetic field. However, the loss factors decrease in higher modes with increase in magnetic field.

Rajamohan et al (2012) analyzed the dynamic characterization of axially non-homogenous MR fluids based multilayer beam. The properties of different configurations of a non-homogeneous MR fluid beam were evaluated to investigate the influences of the location of the various MR fluids for various boundary conditions. Natural frequency and loss factors corresponding to various modes were evaluated under different magnetic field intensities and the effect of location of the fluid treatment on deflection mode shapes was also investigated. Yeh (2013) studied the free vibration characteristics of a magneto rheological elastomer based sandwich plate. The loss factor and the natural frequencies of the sandwich plate were evaluated under various magnetic fields.

2.7. MOTIVATION, OBJECTIVES AND ORGANIZATION OF THESIS

From the above literature reviews, it could be understood that controllable rheological fluids provides the significant potential effects in the structural vibration control. Lot of experiments and analytical studies have been explored by many authors in order to reduce the vibration through lumped MR/ER dampers. However, very limited number of studies has been carried out in the structural vibration control applications. The distributed control force throughout the sandwich structures could be achieved by embedding MR fluid layer between two layers. It can facilitate structure vibration control over a broad range of frequencies through variations in distributed stiffness and damping properties in response to applied magnetic field. It can be concluded from the above literature review that the properties of the sandwich structures embedded with ER/MR fluid and isotropic material as the face layer have been investigated in large number of studies. However, the effectiveness and the evaluation of the dynamic properties of the sandwich structures with MR fluid embedded between the composite plates have not yet been explored.
The objective of the proposed research is to perform the fundamental investigation on the dynamic characteristics of a fully and partially treated laminated composite Magnetorheological fluid sandwich plate and design optimization of the partially treated MR sandwich beam in order to identify optimal locations of the MR fluid segments to maximize the natural frequencies. The specific objectives of the proposed study are:

a). Formulate a mathematical model of a fully treated laminated composite MR fluid sandwich plate using finite-element formulation, and to investigate the dynamic characteristics of the laminated composite MR fluid sandwich plate for different boundary conditions as a function of the applied magnetic field.

b). Fabricate prototypes of fully treated laminated composite MR fluid sandwich plate and test to characterize the dynamic properties and validate the finite element method.

c). Formulate a relationship for the complex shear modulus and loss modulus of the MR fluid as a function of applied magnetic field using a plate and plate geometry type of stain controlled MR rheometer.

d). Formulate mathematical models of partially treated laminated composite MR fluid sandwich plate with different boundary conditions and different size and position of MR segments and evaluate its dynamic characteristics as functions of the applied magnetic field. Experiments are also conducted to validate the partially treated laminated composite MR fluid sandwich plate.

e). Formulate an optimization problem to determine optimal locations of the MR fluid segments using genetic algorithm technique to maximize the natural frequency and loss factor corresponding to individual and multiple modes of transverse vibration under various boundary conditions.

The organisation of the dissertation consists of six chapters. The first chapter provides an introduction about the properties and behavior of controllable fluids, laminated composites and sandwich construction in the semi-active control applications.
The second chapter summarizes the highlights of relevant literature studies on laminated composites, controllable rheological fluids, modes of operation, modeling, dynamic characteristics of the MR and ER fluids, and their potential applications for attenuation of vibration of vehicles and structures, and the analytical and experimental methods developed. The scope of the research work is formulated on the basis of the literature reviews.

The third chapter investigates the dynamic properties of a laminated composite MR fluid sandwich plate. The governing differential equations of motion of a MR fluid sandwich plate is presented in finite element formulation. The validity of the developed finite element formulation is demonstrated by comparing the results in terms of natural frequencies derived from the present finite element formulation with those of available literatures and the laboratory measured data. Furthermore, a relationship between the magnetic field and the complex shear modulus of the MR materials in the pre-yield regime is presented on the basis of the MR Rheometer measured data. The various parametric studies are also performed to investigate the effect of magnetic field, thickness of MR fluid and ply orientation on the variation of natural frequencies and loss factor of the MR fluid composite sandwich plate under various boundary conditions. Furthermore, the free and forced vibration response of a MR fluid composite plate is investigated.

The fourth chapter investigates the vibration analysis of a partially treated laminated composite MR fluid sandwich plate. The governing differential equations of motion for a partially treated laminated MR fluid sandwich plate are presented in finite element formulation. The validity of the developed finite element formulation is demonstrated by comparing the results in terms of natural frequencies derived from the present finite element formulation with the experimental measurements. Various configurations of a partially treated laminated composite MR fluid sandwich plate are considered to study the effect of location and size of the MR fluid segment under various boundary conditions. The free and forced vibration responses of the various configuration of a partially treated laminated composite MR fluid sandwich plate are also analyzed.
The fifth chapter focuses on the multi objective optimization of a partially treated laminated composite MR fluid sandwich plate. The significance of the location of MR fluid segments is particularly discussed in terms of natural frequencies and loss factors for different boundary conditions. Genetic algorithm is used to solve the multi objective optimization problem. Sixth chapter describes the overall conclusion of the entire research work.