Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 52-10 (2019) 388–393

Micro-Piezoelectric Actuator Vibration Control using Electrorheological Fluid Active Support: Experimental Study

S. S. Djokoto*, E. Dragašius **, V. Jūrėnas *, M. Agelin-Chaab***

** Dept. of Automotive, Mechanical and Manufacturing Engineering, Faculty of Engineering and Applied Science University of Ontario Institute of Technology, 2000 Simcoe Street, North, Oshawa, Canada ON L1H 7K4*
(e-mail:sylvester.djokoto@uoit.ca; martin.agelin-chaab@uoit.ca).
*** Dept. of Production Engineering, Kaunas University of Technology, Studentu 56, 51424, Kaunas, Lithuania (e-mail:egidijus.dragasius@ktu.lt)*
**** Institute of Mechatronics Engineering Kaunas University of Technology, Studentu 56, 51424, Kaunas, Lithuania, (e-mail:vytautas.jurenas@ktu.lt)*

Abstract: The paper investigated vibration control of micro piezoelectric actuator (MPA) using an electrorheological fluid (ERF) active support. In this era of micro-mechanical systems, technological advancement requires an effective way of damping these microstructures. MPA is used in micro air vehicles and micro-robotics in general. Utilization of piezoelectric cantilever beam and ERF as a damper presents a novel driving technique. The damping characteristics of the MPA by subjecting the system to unit excitations were investigated experimentally. The experimental results compared damping ratios of the free vibration of the MPA with and without ERF, MPA with non-activated ERF support and MPA with activated ERF support. It was concluded that when there is no electric field applied to the ERF the damping ratio is higher than when an electric field is applied.

Keywords: Electrorheological fluid, Micro-piezoelectric actuator, Squeeze mode, Damping, MEMS

1. INTRODUCTION

The use of Electrorheological Fluid (ERF) has gained a significant over the years in vibration control of flexible structures. Chih-Jer et al., 2017 proposed an ERF-based smart structure, where the stiffness and the energy dissipation characteristics of the structure are controlled (Chih-Jer et al, 2017). Their work showed an experimental study of a variety of shear configurations based on sandwich beam structures. The idea has been applied to ERF based mount to vibration control in automotive engineering applications. Petek et al. 1992 also proposed actively controllable damping characteristics using the ERF engine mount (Petek et al. 1992).

The development of microsensors using in electrical, electronic and biomedical engineering. From automotive manifold pressure and airbag sensors to biomedical analysis, the range and variety are vast. Research shows that pressure sensors and ink-jet nozzles in general accounts for more than two-thirds of the overall micro-transducer/sensors in the market share. Future predictions indicate that the mechanical microsensor market will continue to expand (http://www.nexus-mems.com).

The inertial sensors in microelectromechanical systems (MEMS) provides a small footprint with sensitivities that are either comparable or exceed any macro sensor, along with the capability of mass production and low unit cost. These sensors apply compliant micro flexures attached to a proof mass that displaces in response to an environmental acceleration. Many transduction mechanisms have been developed that convert the displacement into a measurable electric signal and include thermal, piezoresistive, piezoelectric, optical, and capacitive methods. (Beeby et. al. 2004).

Squeeze-film damping is one of the methods of controlling vibrations in MEMS. The characteristic squeezed films in MSMS devices have been designed using various materials such as electrate, silicon, air polymers and many more. The use of smart fluids and elastomers like Magnetorheological fluid (MRF), Magnetorheological elastomer and ERF as squeezed film damping materials have in recent times found their way into MEMS.

Previous and related research by, Hong et al. (2003) studied the use of ERF as actuators or dampers for vibration suppression and as a piezoelectric ceramic's vibration responder. High voltage is applied to ERF forming a colloid. The change in fluid properties by the application of the voltage alters the dynamic characteristics of the damper due to the amplitude and frequency of vibration (Hong et al. 2003).

Coulter et al 1989. studied the vibration characteristics of a beam sandwiched with ERF. The study was about transverse excitation applied to the beam to obtain the resonant frequencies and loss factors of the beam. It was found out that the resonant frequencies increase slightly with the electric field strength, and the damping loss factor decreases with the modal number and increases with electric field strength (Coulter et al. 1989).

This research presents a unique area of design where ERF was used as active support for a micro piezoelectric actuator (MPA) used MEMS switch. Surface micro-machined

10.1016/j.ifacol.2019.10.062

electrostatically actuated micro-switch is based on the design presented by Ostasevicius et. al. 2005 as shown in Fig. 1 (Ostasevicius et. al. 2005). This micro-device belongs to a class of MEMS and is predicted to be one of the few MEMS-based products to be commercialized over the next 5 years (Grace et. al. 2002).

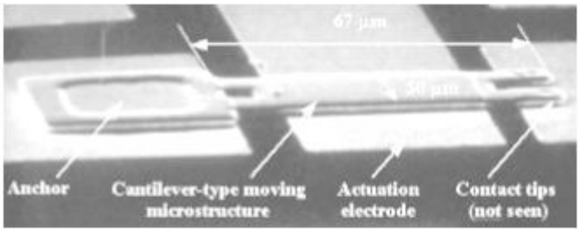

Fig. 1 Surface-micromachined electrostatically actuated microswitch (Ostasevicius et. al. 2005)

The use of an active or semi-active damper could achieve this requisite functionality. Active damping is typically characterized by having an energy input for actuation and a semi-active system is characterized by having a variable damping ratio modified in a closed loop configuration across a wide bandwidth (Savaresi et. al 2010).

A contact-type piezoelectric transducer acting as a micro power source for MEMS sensors by harvesting energy from ambient vibrations source was proposed in another research work. The modelled device is made of a fluid-structure interacting a viscous air damper was manifested in the form of squeeze-film damping governed by the nonlinear compressible isothermal Reynolds equation. The output results were influenced by structural and base excitation parameters as well as the effect of the surrounding pressure on generated voltage, (Daukševičius et. al. 2010).

The goal of this research work is to present an experimental study of controlling vibrations in the MPA using an ERF active support. The study further highlighted the squeeze damping effect of the ERF on the dynamic characteristics of the MPA *and* the non-linear interaction of the viscous ERF in the squeeze-film mode. The results demonstrated that when there is no electric field applied to the ERF the damping ratio is higher compared to when an electric field is applied.

Analysing the vibration characteristics rheological systems are very laborious and challenging to conduct experimentally due to the non-linearity nature of the fluid (pre-yield and post-yield stages). This is due to the flow characteristics of these smart fluid behaving like a Newtonian fluid.

The application of the electric field to the ERF changes the behaviour of the fluid which behaves more similar to Bingham plastic fluid behaviour as shown in Fig. 2 and 3.

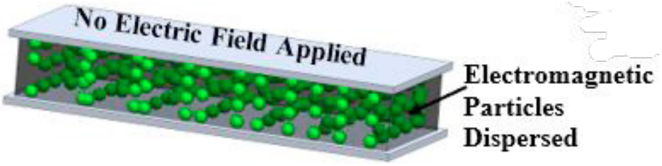

Fig. 2 Characterizing of smart fluid without applying an external field

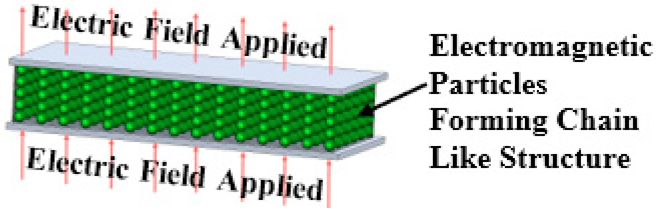

Fig. 3 Characterizing of smart fluid by applying an external field

The change in the electric field changes the flow resistance of the ERF and ultimately controls the damping forces (Petek et.al.1992). The squeeze film mode features a time-varying electrode gap processing the ERF vertically. Research has shown that a squeeze film mode damper has some good properties (Petek et.al.1992).

2. DESIGN OF MICRO-PIEZOELECTRIC ACTUATOR, ERF-DAMPING SYSTEM

2.1 ERF Modelling

ERF exhibits the characteristics of a Newtonian fluid in an ideal situation (Nakamura et. al. 2004). In this situation the particle-type ERF which is a colloidal fluid of the particle dispersion type as shown in Fig.2 and 3. The ERF active support in this study was analysed in the squeezed-mode. From Fig.6 the gap between the electrodes with a vibrating cantilever beam and a normal force squeezes the ERF on impact. It can also be seen from Fig. 6 that the lower electrode is fixed to the base plate, while the upper electrode, in this case, is the vibrating cantilever which is displaced in an upward and downward motion. The device exhibits a damping force caused by the viscosity resistance of the ERF when an electric field is not applied to the ERF. By the application of voltage to the ERF, an electric field is generated through the gap between the bottom and the vibration electrodes. Additional damping is produced due to the yield strength of ERF. (Jolly et.al. 1996). The relations to estimate the characteristics of a squeeze-mode ERF damper as follows:

$$F_{damping}(t) = F_v(t) + F_{ERF}(t) \tag{1}$$

where $F_{damping}(t)$ is the total damping force. $F_v(t)$ is the viscous damping force and $F_{ERF}(t)$ is the controllable damping force associated with an applied electric field. These damping forces are defined by the following equations:

$$F_v(t) = \frac{L\mu w^4}{[h_0+h(t)]^3}\dot{h}(t) \tag{2}$$

$$F_{ERF}(t) = \frac{Lw^3}{[h_0+h(t)]^3}\tau(E)sgn\left(\dot{h}(t)\right) \qquad (3)$$

Where $h(t)$ and $\dot{h}(t)^{\cdot}$ are the displacement between the electrode and relative velocity of the cantilever beam, respectively. h_0 is the initial gap between the electrodes L and w are the length and width of the electrode respectively and μ is the basic viscosity of the ERF when the electric field is zero. $\tau(E)$ is the applied voltage to yield stress of the ERF According to the structure of the proposed ERF damper, the applied electric field is as giving as (Brennan et. al 1995):

$$E(t) = \frac{V_0(t)}{h(t)} \qquad (4)$$

where $V_0(t)$ is the applied voltage

2.2 Dynamic response of MPA System

The motion of the MPA is represented as a single degree of freedom (SDOF) forced harmonic oscillator expressed as (Dragašius et. al 2012):

$$\ddot{h}(t) + (c_{eff}/m)\dot{h}(t) + (k_{eff}/m)h(t) = F_p(t)/m \quad (5)$$

where $c_{eff} = c_{beam} + c_{ERF}$ – total effective damping of the system; $k_{eff} = k_{beam} + k_{ERF}$ – total effective stiffness the of the system, $F_p(t)$ – piezoelectric force

where k_{beam} the stiffness of the free vibrating cantilever beam contact which expressed as (Kim et.at. 2009):

$$k_{beam} = \frac{3EI}{l_b^3} \qquad (6)$$

l_b is the free (vibrating) length of the beam. The flexural rigidity of the beam, EI, can be expressed as

$$EI = \frac{E_{sh}w(t_{sh}^3 - 3t_{sh}^2 a + 3t_{sh}a^2) + E_p w(t_p^3 + 3t_p^2 a + 3t_p a^2)}{3} \qquad (7)$$

Where

$$a = \frac{E_{sh}wt_{sh}^2 - E_p wt_p^2}{2(E_{sh}wt_{sh} + E_p wt_p)} \qquad (8)$$

where $E_p = 1/S_{11}^E$ is Young's modulus of the piezoelectric layer, with S_{11}^E, w and t_p are the piezoelectric compliance, the width of the beam and thickness of the piezoelectric layer, respectively. E_{sh}, and t_{sh} are Young's modulus and thickness of the shim.

The effective mass $m_{eff} = m_{beam}$

where the mass m_{beam} of the vibrating beam is expressed as;

$$m_{beam} = (2\rho_p t_p + \rho_{sh}t_{sh}) \times l \times w \qquad (6)$$

where ρ_p the piezoelectric material density and ρ_{sh} as the density of the shim.

Finding the stiffness (k_{ERF}) of ERF particle chain produced by ERF is calculated using Hooke's law, as shown below (Kaluvan et al. 2014)

$$k_{ERF} = \left|\frac{\partial F_{ERF}}{\partial y}\right| = \left(Lw\tau(E) + \frac{2\mu Lw}{h(t)}\right) \qquad (7)$$

The resonant frequency of the active MPA - ERF stopper is given as:

The natural frequency of the MPA under a single degree of freedom (SDOF) can be expressed as,

$$\omega_n = \frac{1}{2\pi}\sqrt{\frac{k_{eff}}{m_{eff}}} \qquad (8)$$

From the free vibration test of the MPA, the logarithmic decay ratio was determined as per the following formula (Parameswaran, et al. 2013):

$$\delta = \frac{1}{n}ln\left(\frac{X}{X_{n+1}}\right) \qquad (9)$$

The logarithmic decay ratio is also written as:

$$\delta = \frac{2\pi\varepsilon}{\sqrt{1-\varepsilon^2}} \qquad (10)$$

Upon solving Eqn. (10), the following relation for damping ratioε was obtained:

$$\varepsilon = \frac{c}{c_c} = \frac{c}{2mf_n} = \frac{\delta}{\sqrt{4\pi^2+\delta^2}} \qquad (11)$$

Eqn. (6) will give the following relation for damping factor c

$$c = \frac{2\delta\sqrt{km}}{\sqrt{(\delta^2+4\pi^2)}} \qquad (12)$$

3. EXPERIMENTAL SET-UP

Figure.4 shows the geometric structure of the proposed micro-cantilever damping system. The system is made up of a vibrating bimorph piezoelectric cantilever beam with the end tip impacting on a layer ERF. The layer of ERF is placed on an electrode plate under the tip of the cantilever was 5ml thick. The ERF solidifies when it is subjected to an electric field, serving as a damper or stopper for the vibrating cantilever. The solidification of the ERF, however, depends on the intensity of the electric field applied. The contact between ERF and the tip MPA provides a high coefficient of compensation. The excitation of the clamped cantilever displaced downwards where the tip of MPA comes into contact with ERF in the squeeze mode. Similarly, the displaced upwards movement separates the cantilever from the ERF.

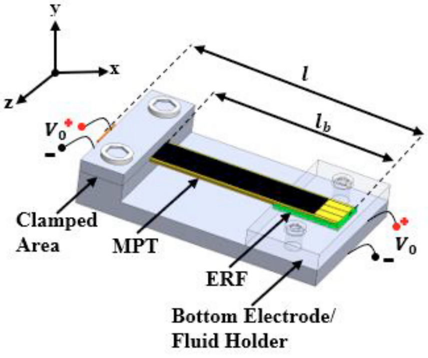

Fig. 4 Proposed ERF-Active Support MPA System

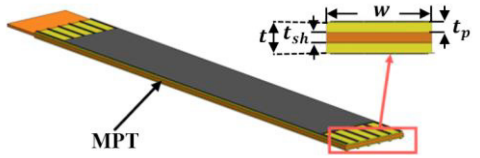

Fig. 5 Schematic of Micro- Piezoelectric Cantilever Beam

Fig. 6 Squeezed ERF film between a fixed bottom and vibrating electrode

Figure. 7 shows the setup for testing for the fabricated vibration control of piezoelectric cantilever beam using active support with ERF. A signal generator (Tabor WW5064) and a power amplifier (EPA-104) are connected to the clamped piezoelectric beam, generating an excitation frequency of 10Hz-200Hz. In order to activate the ERF, a high-voltage, the inverter of model CCF122C with variable power DC supply 18V 3A was connected to the copper bottom plate electrode that holds the ERF. The initial gap h_0 between the bottom, copper plate electrode and piezoelectric bimorph cantilever without vibration were set at 0.5mm as shown in Fig. 6. From equation (4), the vibrating piezoelectric cantilever beam and the intensity of the electric field determine the gap distance. In this experiment, the formula in equation (4) was used to determine the electric field. The parameters for the voltage $V_0(t) = 1000V$, giving an electric field $E(t) = 2kV/mm$. A laser displacement sensor (Keyence LK G82) was set above the vibrating cantilever beam. This device measures the displacement of the input excitation to the cantilever beam's free end. An analogue voltage signal from this device is sent to a controller (Keyence LK-G3001P) which then processed and filtered. A PiscoScope-3424 is connected to the laser controller which sends vibration signals to a connected computer.

Table 1 Geometries and material properties of the model MPA

Description	Value	Symbol
Free (vibrating) length	36 mm	l_b
Width of MPA	7.2 mm	w
Total thickness of MPA	0.78 mm	t
Shim thickness	0.28 mm	t_{sh}
Ceramic thickness of MPA	0.25mm	t_p
Piezoelectric layer density	8000 kg/m^3	ρ_p
Shim layer density	1800 kg/m^3	ρ_{sh}
Shim layer modulus of elasticity	120e9 N/m^2	E_{sh}
Piezoelectric compliance	15.8e-12 m^2/N	S_{11}^E

Table 2 Characteristics of the model squeeze-mode ERF-Active Support MPA system

Property	Value	Symbol
Base Fluid	silicone based	
Density (	1.3e3 (kg/m^3)	ρ_{ERF}
Viscosity at 30^{o}C	0.11 Pa.s	μ
Initial gap	0.5 mm	h_0
Length of electrode	10 mm	L
Total length of MPA	50 mm	l
Layer of ERF	5 ml	

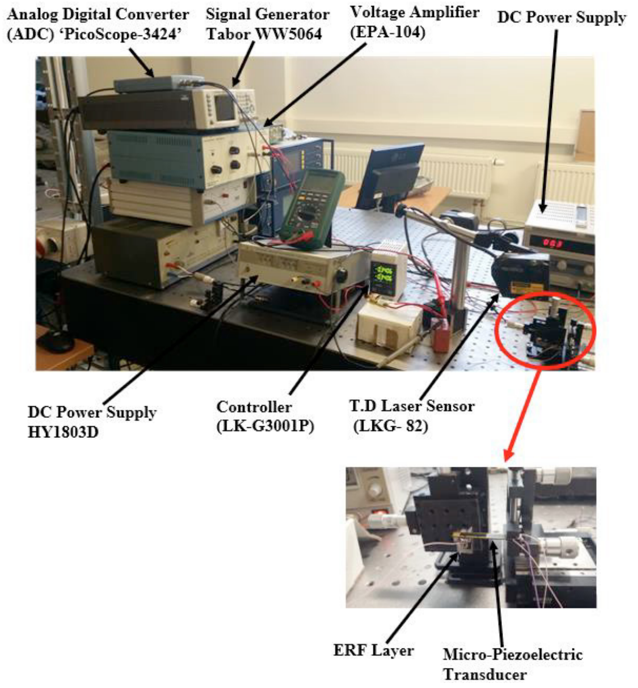

Fig. 7 Photograph of Experimental set-up for ERF-Active Support MPA System

4. RESULTS AND DISCUSSION

The curves for the free vibrating in Fig 8, 9, and 10 correspond to the MPA freely vibrate without the application of ERF stopper, a non-activated ERF support and the MPA with an activated ERF active support respectively. The results show that the beam's damping increases scientifically with the application of an electric field to the ERF. The MPA was excited at 203 Hz. The rate of decay of the response in the free-vibration plots can be described in terms of the damping ratio ε given in equation (11). The free vibration response of the MPA without fluids showed a damping ratio of 0.040. There was a decrease in damping when the ERF layer was applied but no electric field was applied, the damping ratio calculated was 0.027. A further decrease of 0.023 damping ratio was calculated for ERF with the application of the electric field. The results from this experimental study compared to many studies of using a sandwiched smart fluid like MRF and ERF cantilever beam. One of such examples was reported by (Berg et. al. 1996).

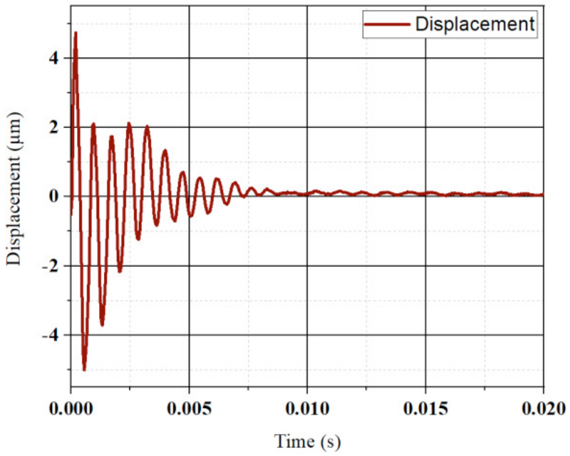

Fig. 8 Free-vibration responses of MPA system without an ERF applied

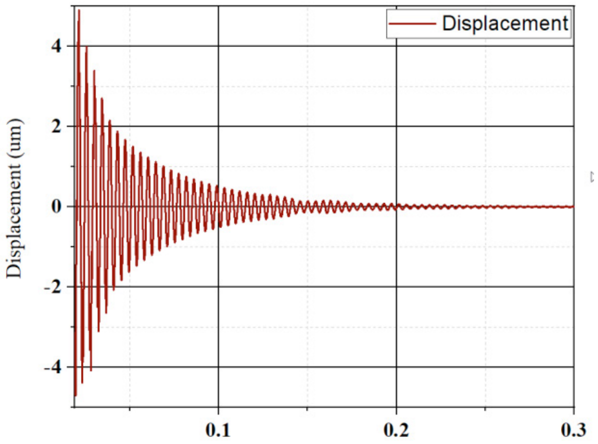

Fig. 9 Free-vibration responses of ERF-Active Support MPA system without an applied electric field

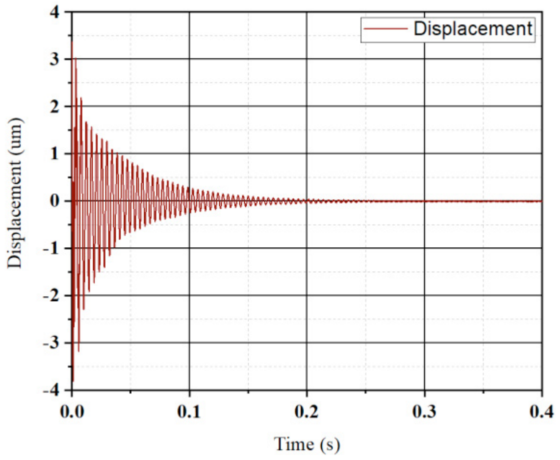

Fig. 10 Free-vibration responses of ERF-Active Support MPA system with an applied electric field

6. CONCLUSIONS

In this paper, an experimental study was conducted to investigate the squeeze-mode damping effects by placing the ERF layer serving as active support under an MPA. The damping characteristics of the free vibrating MPA was investigated. The experimental result compared results for the free vibrating MPA without the ERF support, MPA with non-activated ERF support and MPA activated ERF support. It was concluded that when there is no electric field applied to the ERF the damping ratio is higher than when an electric field is applied. This work demonstrated that squeezed mode film damping could be used for microstructural damping to control vibrations.

REFERENCES

Beeby, S. P., Ensel, G., and Kraft, M., (2004), "MEMS Mechanical Sensors," *Artech House*, Boston, pp. 173-207

Berg, C. D. Evans, L.F. and Kermode, P.R. (1996) “Composite Structure Analysis of a Hollow Cantilever Beam Filled with Electrorheological Fluid”, J of Intelligent Material Systems and Structures,7, pp 494-502.

Brennan, M J, Day M J and Randall R J, (1995) An electrorheological fluid vibration damper, *Journal of Smart Mater. Struct*. 83 -92.

Chih-Jer, L., Chun-Ying, L and Ying L, (2017) “Vibration Control Design for a Plate Structure with Electrorheological ATVA Using Interval Type-2 Fuzzy System”. *Appl. Sci*, 7, 707; doi:10.3390/app7070707

Coulter, J. P. and T. G. Duclos. (1989). "Applications of Electrorheological Materials in Vibration Control", *Proc. 2nd Int. Conf. on ER Fluids*, Raleigh, NC, pp. 300-325

Daukševičius, R. Kulvietis, G. Ostasevicius, V. and Milasauskaite, I. (2010) “Finite element analysis of piezoelectric microgenerator towards optimal configuration”. *Procedia Engineering* 5 1312–1315 Linz, Austria

Dragašius, E., Jūrėnas, V., Mačiukienė V., and Navickaitė, S., (2012), “Investigation of magneto-rheological fluid parameters using cantilever-type piezoactuator” *Journal of Vibroengineering*. Vol.14, Issue 1. ISSN 1392-8716

Grace, R. H, (2002) “Commercialization issues of MEMS/MST/Micromachines, an updated industry report card on the barriers to commercialization,” Proceedings of Sensors Expo & Conference, Boston, September 2002.

Hong.T., Xiaopeng Z., and Shu L, (2003). Applications of Electrorheological Materials in Vibration Control", *Smart Materials and Structures J*, pp. 347-354

Jolly, M.R. and Carlson, J.D. 1996. ‘‘Controllable Squeeze Film Damping using Magnetorheological Fluid,’’ *ACTUATOR 96, 5th International Conference on New Actuator*, pp. 333–336.

Kaluvan., S., Shah K. and Choi, S-B, (2014). ‘A new resonant based measurement method for squeeze mode yield stress of magnetorheological fluids’ *Smart Mater. Struct*. 23 115017

Kim H., Tadesse Y. and Priya S. ‘Piezoelectric Energy Harvesting’. *Energy Harvesting Technologies*. New York: Springer, 2009 41-77.

Nakamura, T., Saga, N. and Nakazawa, M. (2004). ''Variable Viscous Control of a Homogeneous ER Fluid Device Considering Its Dynamic Characteristics,'' Journal of Mechatronics, 14:55–68.

Nexus MST market analysis, http://www.nexus-mems.com

Parameswaran A.P., Pai A.B., Tripathi, P.K. and Gangadharan K.V. (2013), 'Active Vibration Control of a Smart Cantilever Beam on General Purpose Operating System', *DEF. SCI. J.*, vol. 63, No. 4

Petek N K (1992) An electronically controlled shock absorber using ER fluid *SAE Trans*. paper 920275

Ostasevicius, V., Daukševičius, R., Tamulevicius, S., Bubulis, A., Grigaliunas, V., and Palevicius, A. (2005) "Design, fabrication, and simulation of cantilever-type electrostatic micromechanical switch," *Proc. SPIE 5763, Smart Structures and Materials 2005*: Smart Electronics, MEMS, BioMEMS, and Nanotechnology, doi:10.1117/12.599111

Savaresi, S.M., Poussot-Vassal, C., Spelta, C. SenameO and Dugard, L. (2010). Semi-Active Suspension Control for Vehicles, *Elsevier-Butterworth Heinemann*, ISBN13: 978-0-08-096678-6, 245 pages