A numerical investigation of the performance analysis of an electrorheological hydrostatic journal bearing

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***Abstract*— This work describes a theoretical study concerning the performance characteristics of an electrorheological hydrostatic journal bearing. The hydrostatic journal bearing consists of four hydrostatic bearing flat pads fed by capillary restrictors. A negative electrorheological (NER) fluid is a Newtonian fluid with a viscosity which decreases when an electric field is applied, and which can restore its property when the field is removed. A reversible change in viscosity occurs in milliseconds with application of an electric field. Therefore, these fluids are suitable for the real-time control of vibration and vibration damping. A linear modeling was performed in order to study the performance characteristics of a capillary compensated four-pad hydrostatic journal bearing in order to investigate the effect of negative electrorheological fluids and static eccentricity ratio on carrying load capacity, flow, and the dynamic characteristics (stiffness and damping) of an electrorheological hydrostatic journal bearing. An electrorheological fluid consists of a suspension of micron-sized particles dispersed in a dielectric liquid. The discussion of results includes some thoughts on future trends. The results presented in this work are expected to be quite useful to the bearing designers.**

Keywords—Electrorheological fluid, Hydrostatic bearing, Squeeze film lubrication, Newtonian fluids, Reynolds equation, Journal bearing dynamics.

Introduction

In rotating machinery, more performance enhancement is in demand in terms of speed and accuracy. However, these machines face to a vibration problems caused by mass imbalance, bearing defect, and shaft misalignment, especially in high speed rotating machinery. For subject of vibration suppress, there are three kind of control: passive, active and semi active. The hydrostatic squeeze film damper HSFD is a kind of bearing damper that has been used in the process industry to reduce vibration. It generates its damping force capability in reaction to dynamic journal motions squeezing a thin film of lubricant in the clearance between a stationary housing and a whirling journal. However, for rotors operating at rotational speed beyond critical speeds, a semi-active control to reduce vibrations is favourable in terms of stability and performance [1]. Smart hydrostatic squeeze film damper using an electrorheological fluid ER as a smart material is effective in reducing rotor vibration when the rotor passes through the critical speed.

An electrorheological fluid consists of micron-sized particles dispersed in dielectric liquid. Under the action of electric field, the particles in the ER suspension are polarised and the interaction between the resulting dipoles causes the particles to form fabricated structure aligned with the electric field. A gel-like phase is obtained at zero shear rate which is broken only when imposing a shear stress greater than a threshold value (the yield stress). The rapid transformation (in milliseconds) of the ER fluid from a liquid phase to a solid phase leads to a dramatic and reversible change in its rheological properties (viscosity, yield stress, shear modulus, etc.), where the apparent viscosity increases by factor as high as 10^5 [2-5].

Since the innovation of the ER fluid in 1947 by Winslow [6], attention has been paid in order to increase the rheological properties induced by electric field [2-7]. This effect is termed the positive ER effect. Wen et al (2003) [8] have reported the giant electrorheological effect in a suspension of nano-particles, where the yield stress up to 130 kpa.

In 1995, Boissy et al [9] found in their studies that the apparent viscosity of the ER suspension decreases as the external electric field increases. This phenomenon is totally opposite to the positive ER effect, and termed the negative ER effect.

Negative ER effect could be used in the industry when a controllable decrease of the viscosity is expected. The advantage of the viscosity change of negative ER fluids is that the behavior remains Newtonian [10]. Various other systems were also found to display the negative ER effect [11-15]. Kimura et al (1998) [12] studied the ER effect in several UPPG (urethane-modified polypropylene glycol) /DMS (dimethylsiloxane) blends, they found that the sign positive or negative and the strength of the ER effect can be controlled by changing the temperature and viscosity ratio of UPPG and DMS. Lobry and Lemaire (1999) [13] obtained a decrease of the viscosity in a suspension making use of Quincke rotation: the spontaneous rotation of insulating particles (PMMA) suspended in a weakly conducting liquid when the system is submitted to a DC electric field. They found for the first time that an apparent zero viscosity is attained. This system can be tuned in a negative range when the system is submitted to a DC field, or in a positive range where the external field frequency is increased for few hundred Hertz. Mitsumata and sugitani (2004) [14] showed that the negative ER effect is influenced by the swelling of the particles. Cetin et al (2012) [15] investigated the properties of the negative ER effect in a suspension of colinamite and polyindene dispersed in silicone oil. They found that the negative ER response was converted to a positive one by addition of non-ionic surfactant and they showed that these materials have the potential to be used for vibration damping when doped with appropriate surfactants.

Because of their fast response time and controllable shear viscosity, many ER devices have been reported and patented such as clutches, shock absorber [16], damping devices [17], micro fluidic chips [18], haptic devices [19], etc. One very promising application is the use of ER fluids for vibration control of high speed lubricated rotor bearing systems, based on the electrical alteration of stiffness and damping. Nikolajsen and Hoque (1990) [20] were first to investigate the performance of ER squeeze film damper and to recognize its efficiency. Pecheux et al (1996) [21] investigated numerically a shaft bearing assembly with a squeeze film damper using negative electrorheological fluid in order to control the dynamic behaviour of the shaft. They showed that it could be possible to monitor the damping of a squeeze film damper. Ahn et al (1998) [22] described a controllable squeeze film damper that uses liquid crystal LC as a lubricant in rotating machines which can produce anisotropic damping forces in the horizontal and vertical directions. Liquid crystal is an ER fluid that the Newtonian viscosity can be varied by the applied of electric or magnetic field strength. They showed that the liquid crystal is successfully applied to the SFD for the stabilisation of rotating system and the damping force can be controlled by the externally applied field. Nikolakopoulos and Papadopoulos (1998) [23] presented an experiment in a high speed journal bearing with small radial clearance, lubricated with ER fluid. They showed that ER fluids have a substantial effect on the dynamic characteristics of journal bearing operating at high shear rates, even using material with the small yield stress (150 pa) in realistic bearing configuration. Yao et al (1999) [24] studied theoretically and experimentally the application of a new disk type to the vibration suppression of a rotor system. They found that the ER damper can suppress large vibration amplitudes around the critical speed. Seungchul et al (2005) [1] investigated the design and application of an electrorheological fluid damper to semi active vibration control of high speed rotor systems. Bouzidane and Thomas (2007) [10] investigated the dynamic behaviour of a rotor supported by a new hydrostatic journal bearing, and fed with a negative electrorheological fluid. They found that in order to reduce vibratory response of the rotor excited by an imbalance, it is sufficient to use a fluid with a high viscosity in order to obtain a high damping, however, the NER fluid can be activated when operating at speeds higher than critical speed without increasing rotor vibration. On the other hand, using a negative electrorheological fluid (NER) is very efficient when the force transmitted to the base must be reduced. When the rotor operates close to the critical speed, the electric field has not to be activated in order to obtain a high damping. When the excitation speed is higher than 1.4 times the critical speed, the electric field must be activated in order to reduce damping.

The objective of this study is to investigate the static and dynamic behaviour of a four pad hydrostatic journal bearing fed with a negative electrorheological fluid. We present a linear modeling in order to study the effect of the negative electrorheological fluid on carrying load capacity, flow and the dynamic characteristics (stiffness and damping).

Description of hydrostatic journal bearing

In this study, the hydrostatic journal bearing is composed of four identical plane hydrostatic bearing pads, with indices 1, 2 and 3 refer to the characteristics of the upper, left, lower and right hydrostatic bearing pads, respectively (Fig. 1).

Each pad fed with a negative electrorheological fluid by a recess, which is supplied by an external pressure Ps through a capillary restrictor-type hydraulic resistance.

The calculation of hydrostatic journal bearing characteristics is obtained by considering the hydrostatic journal bearing as the juxtaposition of three hydrostatic bearing flat pads. We assume that the fluid flow is incompressible, laminar, isothermal, and steady state.

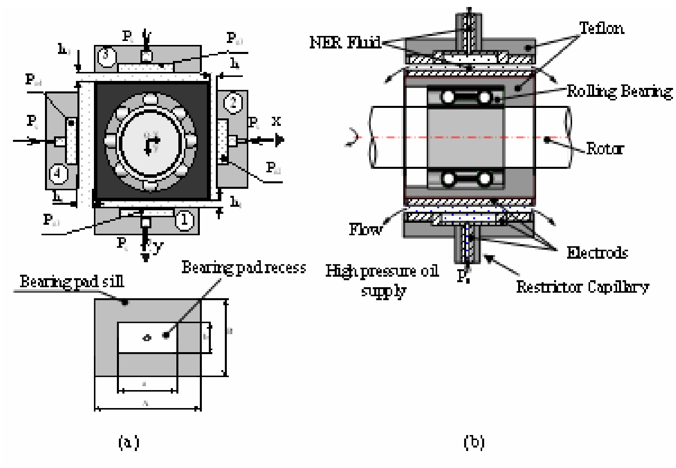


Fig. 1: Hydrostatic journal bearing characteristics

Reynolds equation

The Reynolds equation allows the computation of the distribution pressure Pi(Xi,Zi). This equation can be solved numerically by applying the centered finite differences method, or analytically in case of particular assumption of infinitely long journals. If we assumed that there is no slip between the fluid and pad bearing, the boundary conditions associated with the speed will be as follows (Fig. 2):

On bearing pad: $U_{1i} = 0;\ V_{1i} = 0;\ W_{1i} = 0$

On journal: $U_{2i} = 0;\ V_{2i} = \dot{h};\ W_{2i} = 0$

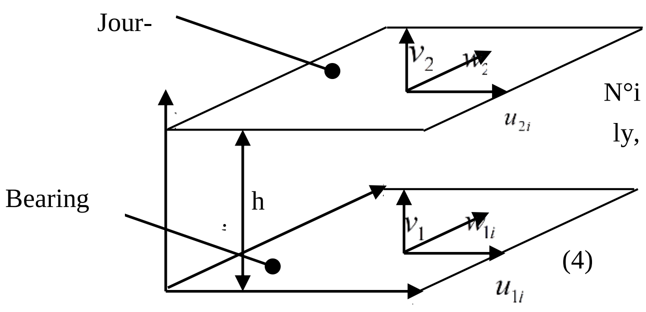


Fig.2. Boundary conditions of hydrostatic journal bearing.

Where U_{1i}, V_{1i} and W_{1i} are the speeds of the surface of the bearing pad N°i and U_{2i}, V_{2i} and W_{2i} are the speeds of the surface of the journal.

With these boundary conditions, and for assumption of incompressible, laminar, isoviscous and inertialess fluid flow frees of cavitations, the Reynolds equation may be written as:

$$\frac{\partial}{\partial x}\left[\frac{h_i^3}{\mu}\left(\frac{\partial P_i}{\partial x}\right)\right] + \frac{\partial}{\partial z}\left[\frac{h_i^3}{\mu}\left(\frac{\partial P_i}{\partial z}\right)\right] = 12\,\dot{h}_i$$

(1)

Where $0 \le x \le A$ and $0 \le z \le B$, P_i is the hydrostatic pressure field of the hydrostatic bearing pad N°i, h_i is the film thickness of the hydrostatic bearing pad N°i, $\dot{h}_i$ is the squeeze velocity of the hydrostatic bearing pad N°i, and μ is the fluid viscosity.

It assumed that the pressure in the recess is constant and equal to P_{ri} and the ambient pressure is null. Thus the boundary conditions of equation () are:

$$P_i(0 \le x \le A, z = 0) = 0,$$

$$P_i(x = 0, 0 \le z \le B) = 0,$$

$$P_i(x_1 \le x \le x_2, z_1 \le z \le z_2) = P_{ri}$$

Recess pressure

The recess pressure for each hydrostatic bearing pad is obtained by resolving the flow continuity equation.

$$Q_{ri} = Q_{si}$$

(2)

Where $Q_{si} = Q_{xi} + Q_{zi} + Q_{vi}$

(3)

Q_{ri} is the flow through an orifice hydraulic resistance, Q_{xi} and Q_{zi} are the fluid flow of the hydrostatic bearing pad N°i in the x_i and z_i directions, respectively, Q_{vi} is the squeeze flow of the hydrostatic bearing pad N°i.

$$Q_{vi} = S_a\,\dot{h}_i$$

(4)

$$Q_{xi} = \int_0^A dx \int_0^{h_i} u_{xi}\,dy;$$

(5)

$$u_{xi} = \frac{1}{2\mu}\frac{\partial P}{\partial x}(y - h_i)y$$

(6)

$$Q_{zi} = \int_0^B dz \int_0^{h_i} u_{zi}\,dy;$$

(7)

$$u_{zi} = \frac{1}{2\mu}\frac{\partial P}{\partial z}(y - h_i)y$$

(8)

Where u_{xi}, u_{yi}, u_{zi} are the flow velocities in the x_i, y_i, z_i directions, respectively.

$$Q_{ri} = \frac{\pi d_c^4}{128 \mu L_c}(P_s - P_{ai})$$
(9)

The negative electrorheological fluid

In this study a negative electrorheological fluid which was reported by Boissy et al [9]. They investigated a suspension of polymethylmethacrylate PMMA (particles diameter $\phi \approx 15\mu m$ and conductivity $\sigma_s = 10^{-14} S/m$) dehydrated during 40 hours in vacuum, dispersed in a mixture of two liquids ($\sigma_L = 3*10^{-10} S/m$), Ugilec T^* (a weakly polar solvent) and mineral oil $TF50^*$ in proportion such as to have a liquid density equal to that of the solid phase. They found that the electric field has a strong influence and for a volume fraction of 30%, the viscosity of the suspension can be decreased by a factor up to about 5.

Fig.3 shows the relationship between the viscosity and the electric field for the negative electrorheological fluid studied by Boissy et al [9].

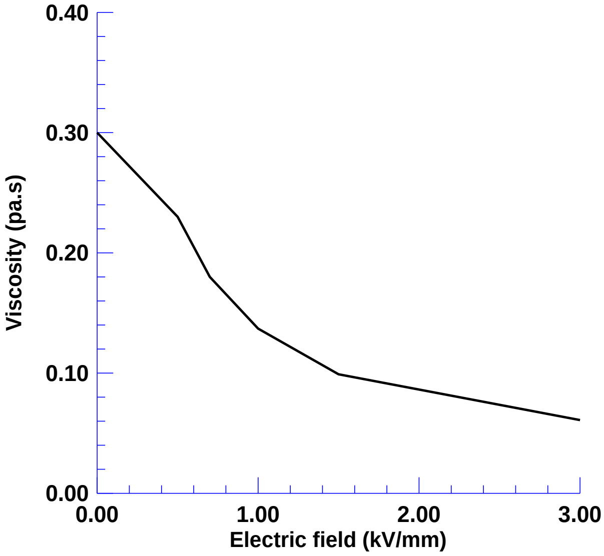


Fig.3. Variation of viscosity with electric field in negative electrorheological fluid.

Analytical results and discussions

The analytical method is used for the calculation of the characteristics by considering the particular assumption of infinitely long journals.

At the point of operation, when the hydrostatic squeeze film damper is in the center position, the following relations are obtained: $h_i = h_0, P_{ri} = P_{r0}, \beta_i = \beta_0$

Where h_0, P_{r0}, β_0 are the film thickness, the recess pressure and the pressure ratio, respectively, at the center position of the hydrostatic squeeze film damper. h_i, P_{ri}, β_i are the film thickness, the recess pressure and the pressure ratio of the hydrostatic bearing pad N°i.

The bearing characteristics are set as follows:

- Bearing pad length ,*A=0.1524 m and B=0.0254* m;
- Recess dimension ratio, *a/A=0.5 and b/B*, is 1;
- The pressure supply, P_s, is 0.1 MPa;
- The viscosity, μ , is 0.05 Pa.s;

Film thickness analysis

As seen in fig.4, the film thickness is studied according to the pressure ratio at the point of operation as the electric field applied E=0 kV/mm. This figure shows that the film thickness decreases when the pressure ratio increases.

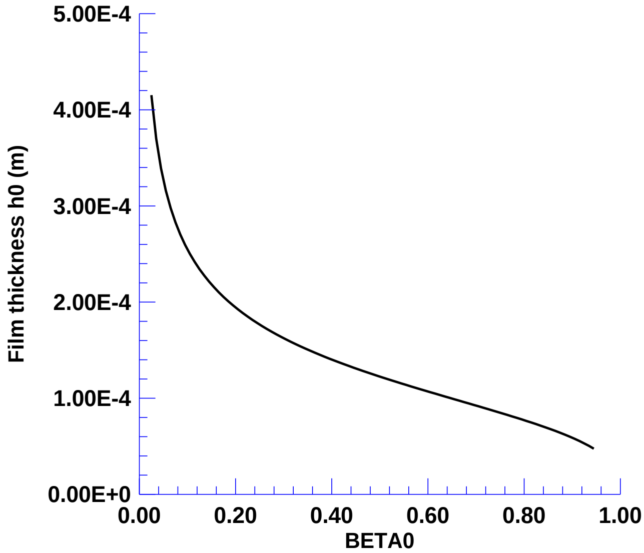


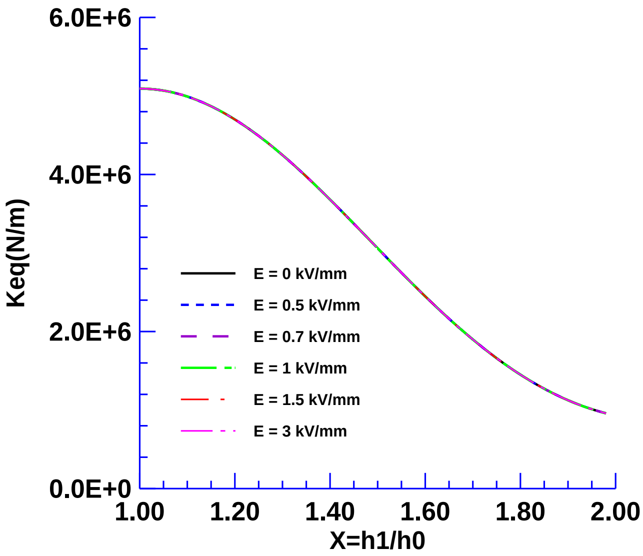
Fig.4. Film thickness versus pressure ratio

Static characteristics analysis

Fig.5 shows the effect of eccentricity ratio and of the electric field on the carrying load capacity. This curve shows that the load capacity increases when the pressure ratio increases. It must be noticed that the electric field has no effect on the load capacity. Fig.6 shows the effect of the eccentricity ratio on the flow rate requirement at the point of operation for different electric fields. The flow rate increases when the electric field increases because the viscosity of the NER fluid decreases when the electric field increases, and as a result, the flow increases since it is inversely proportional to the viscosity.

Dynamic characteristics analysis

Fig.7 shows the influence of eccentricity ratio and of the electric field on the stiffness coefficient at the point of operation. As seen in Fig. 7, there is no effect of electric field on the stiffness coefficient because it is independent to the viscosity. Fig.8 shows the effect of the eccentricity ratio for the different electric fields on the damping coefficient. This curve shows that the damping coefficient increases when the eccentricity ratio increases. On the other hand, the damping coefficient decreases when the electric field increases since it is proportional to the viscosity.



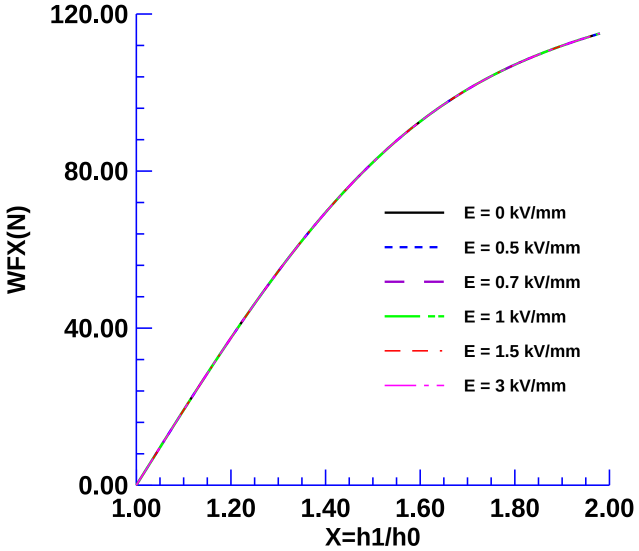


Fig.5. Carriying load capacity versus eccentricity ratio for different electric field.

Conclusions

A linear modeling was performed using analytical methods in order to investigate the effect of negative electrorheological fluids on carrying load capacity, flow, and the dynamic characteristics (stiffness and damping coefficients) of a four-pad hydrostatic squeeze film damper HSFD using a capillary restrictor-type hydraulic resistances . The results can be summarized as follow:

- The electric field has no effect on the carrying load capacity.
- When an electric field is applied, the viscosity of the negative electrorheological fluid decreases and this leads to an increase in the flow rate requirement.
- The stiffness coefficient is not influenced with the application of the electric field.
- The damping coefficient decreases when applying an electric field.

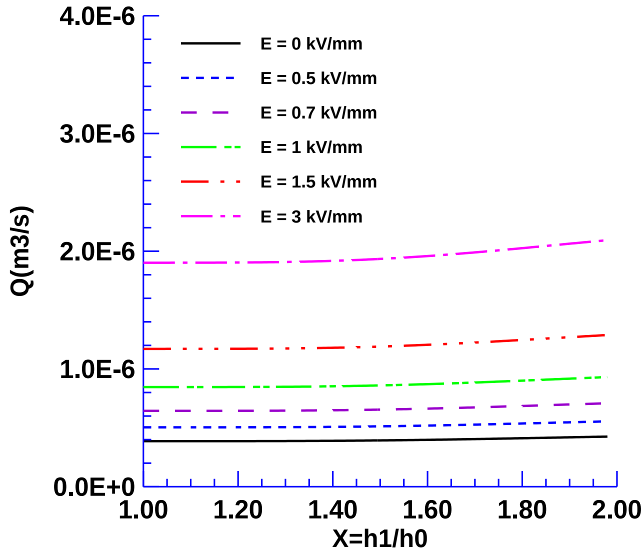


Fig.6. The flow rate versus the eccentricity ratio for different electric field.

Fig.7. The stifness coefficient versus the eccentricity ratio for diffrent electric field.

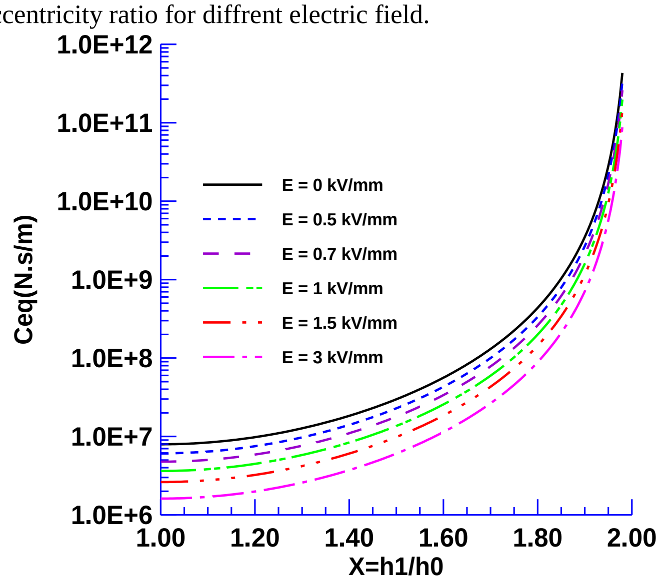


Fig.8. Damping coefficient versus the eccentricity ratio for different electric field

References

[26] Seungchul Lim, Sang-Min Park, Kab-Il Kim, AI vibration control of high-speed rotor systems using electro-

rheological fluid, Journal of Sound and Vibration 284 (2005) 685–703.
[27] A.P. Gast and C. F. Zukoski, Electro-rheological fluids as colloidal suspension, Adv. Colloid Interface Sci. 30 (1989), 153-202.
[28] H. Conrad and A. F. Sprecher, Characteristics and mechanisms of electro-rheological fluids, J. Stat. Phys., 1994, 64, 1073.
[29] T.C. Halsey, Electro-rheological fluids, Science 258 (1992) 761.
[30] **]** H. Block and P. Rattray, Recent developments in ER fluids, in Progress in Electrorheology, edited by K.O.Havelka and F.E. Filisko (Plenum Press, New York, 1995), p. 19-42.
[31] W.M. Winslow, Method and means for translating electrical impulses into mechanical force, U.S. Patent 2417850, 1947.
[32] T. Hao, Electro-rheological suspensions, Adv. Colloid Interface Sci. 97 (2002), 1-35.
[33] W. Wen, X. Huang, S. Yang, K. Lu and P. Sheng, The giant electro-rheological effect in suspensions of nanoparticles, Nat. Mater., 2003, 2, 727.
[34] C. Boissy, P. Atten and J.N. Foulc, On the negative electro-rheological effect, J. Electrostatics 35 (1995), 13-20.
[35] Bouzidane A. and Thomas M., An electro-rheological hydrostatic journal bearing for controlling rotor vibration, Computers and Structures 86 (2008) 463–472.
[36] Young Gun Ko and Ung Su Choi, Negative electrorheological fluids, J. Rheol. 57(6) (2013) 1655-1667.
[37] H. Kimura, K. Aikawa, Y. Masubuchi, J. Takimoto, K. Koyama, T. Uemura, ‘Positive’ and ‘negative’ electro-rheological effect of liquid blends, J. Non-Newtonian Fluid Mech., 76 (1998) 199–211.
[38] L. Lobry, E. Lemaire, Viscosity decrease induced by a DC electric field in a suspension, J. Electrostat 47 (1999) 61-69.
[39] Tetsu Mitsumata, Kousuke Sugitani, Negative Electrorheological Effect of Silicone Gels Containing Barium Titanate, Macromol. Rapid Commun. 2004, 25, 848–852.
[40] Cetin, B., H. I. Unal, and O. Erol, The negative and positive electrorheological behavior and vibration damping characteristics of colemanite and polyindene/colemanite conducting composite, Smart Mater. Struct. 21, 125011 (2012).
[41] W **A** Bullough and N Jakeman, ELECTRO-RHEOLOGICAL (ER) DEVICES - properties, performance and applications, 1998.
[42] **[17]** S. B. Choi, Y. T. Choi, E. G. Chang, S. J. Han, C. S. Kim, Control characteristics of a continuously variable ER damper, Mechatronics 8 (1998) 143-161.
[43] Limu Wang, Xiuqing Gong, and Weijia Wen, Electrorheological fluid and its applications in microfluidics, Top Curr Chem (2011) 304: 91–115.
[44] Han, Y.-M., and S.-B. Choi, Control of an ER haptic master in a virtual slave environment for minimally invasive surgery applications, Smart Mater. Struct. 17, 065012 (2008).
[45] Nikolajsen, J. L. and Hoque M. S., An Electroviscous damper, N89-22898 (1990) 133-141.
[46] Pecheux B., Bonneau O. and Frêne J., Investigation about Electro-Rheological Squeeze Film Damper Applied to Active Control of Rotor Dynamic, International. Journal of Rotating Machinery, Gordon and Breach Science Publishers, 1997, vol. 3, No.1, pp. 53-60.
[47] Young-Kong Ahn, Shin Morishita and Bo-Suk Yang, Directionally Controllable Squeeze Film Damper Using Liquid Crystal, KSME International Journal, VoL 12. No. 6, 1998, pp. 1097-1103.
[48] P.G. Nikolakopoulos, C.A. Papadopoulos, Controllable high speed journal bearings, lubricated with electrorheological fluids. An analytical and experimental approach, Tribology International 31 (1998) 225–234.
[49] G. Z. YAO AND Y. QIU, vibration control of a rotor system by disk type electrorheological damper, Journal of Sound and Vibration (1999) 219(1), 175-188.