Smart fluid

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1. Theme description

A smart fluid, also called electro rheological fluid[1], is a liquid suspension of metals or zeolites which solidifies when electric current is applied to it, becoming fluid again when the current is removed.

Smart fluids can be divided in four main classes:

- electro-rheological (ER) fluids[2];
- magneto-rheological (MR) fluids[3];
- magneto rheological elastomer (MRE) fluids[4];
- electro-conjugate liquids[5].

Since 1960, the engineers tried to develop new devices based on ER smart fluids (vibration damper, flow control waves, etc.), without important results. The turning point was there in 1990, after the discovered of MR smart fluid: indeed, in 2002, suspension damping struts of the Cadillac Seville STS model automobile (based on smart fluids) was discovered[6].

The interest for this kind of technology is considerable and the perspective for a new device based on smart fluids is real.

In the following, a review on smart fluids, with future developments in the close future, is reported.

[1] http://www.businessdictionary.com/definition/smart-fluid.html
[2] w. m. winslow: J. Appl. Phys., 1949, 20, 1137 – 1140
[3] j. rabinow: AIEE Trans., 1948, 67, 1308 – 1315
[4] B. X. Ju, M. Yu, J. Fu, Q. Yang, X. Q. Liu, and X. Zheng, "A novel porous magnetorheological elastomer: preparation andevaluation," Smart Materials and Structures, vol. 21, no. 3, Article ID 035001, 2012
[5] W.-S. Seo, K. Yoshida, S. Yokota, and K. Edamura, "A high performance planar pump using electro-conjugate fluid with improved electrode patterns," Sensors and Actuators A: Physical, vol. 134, no. 2, pp. 606–614, 2007
[6] r. stanway: Mater. World, February 2002, 10 – 12

2. Smart fluids

The article focuses the attention on electro-rheological (ER) and magneto-rheological (MR) fluids. These two kinds of smart fluids have in common the dielectric carrier liquid (such as silicone oil). The difference is in the particle used to make ER or MR fluids, and, consequently, the type of field to apply at the smart fluid to trigger its ability[7].

<u>ER Fluids</u>

ER fluids usually have a kinematic viscosity in the range 10 – 50 centistokes. Into his carrier liquid semi-conducting particles with a diameter within the range 5 – 50 mm are dispersed. The ER fluid is encased between a suitable arrangement of electrodes and, applying an electric field of sufficient intensity, the ER fluid actives its ability. The electric field causes the polarization of particles and chain like structure between the particles: this phenomenon causes a significant increase in the resistance to flow of the ER fluid (virtually instantaneous and completely reversible). The electric field necessary to trigger the phenomenon is up to 4 kV mm^{-1} in the inter-electrode gap, that it usually sizes within the range 0.5–2.0 mm[8].

An example of commercial ER fluids based upon a water free dispersion of polyurethane particles in silicone oil is marketed by the German chemical company Bayer AG. Although the levels of yield stress quoted appeared modest (around 4 kPa maximum) and the electric field strengths high (up to 5 kV mm^{-1} of inter-electrode gap), it is interesting for some commercial organizations.

<u>MR Fluids</u>

MR fluids is a suspension of magnetically soft particles in a carrier liquid of mineral or silicone oil. Particle sizes within the range 0.1 – 10 mm (smaller than those used in ER fluids). The mechanism that produced an increase of resistance to flow is similar to that of ER fluids, only that it is produced by a magnetic field. Quantitatively, a magnetic flux density of less than 1T is generally sufficient to trigger the phenomenon[9].

[7] Smart fluids: current and future developments, R. Stanway, 16 April 2004, Maney for the Institute of Materials, Minerals and Mining
[8] k. weiss, j. d. carlson and j. p. coulter: J. Intell. Mater. Syst. Struct., 1993, 4, 13 – 34
[9] j. d. carlson: in 'Adaptronics and smart structures', (ed. H. Janocha), 180 – 195; 1999, Springer-Verlag.

The key to a good MR fluid is the particle with a large saturation magnetisation. The best available solid particles are alloys of iron and cobalt (with a magnetization of about 2.4 T). However, these alloys have a prohibitive cost, so pure iron particles are invariably used in commercial MR fluids. Pure iron particles have saturation magnetizations of around 2.15 T (weaker than using alloy particles).

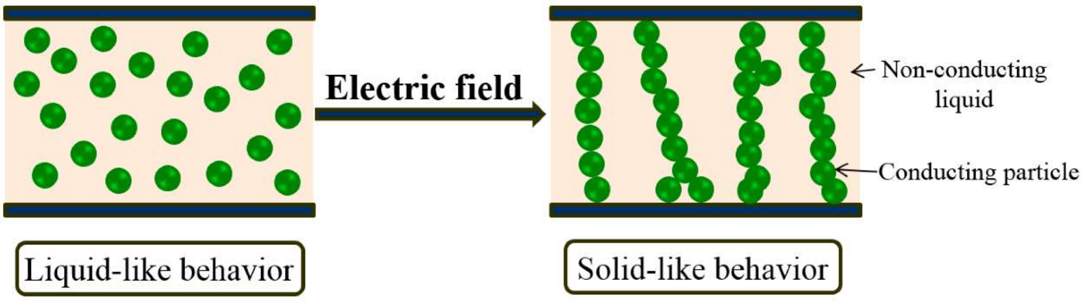

Figure 1. ER fluids with and without electric field.

3. Macroscopic model

In first approximation, both ER and MR fluids can be described by Bingham plastic behavior[10] (Figure 2). When there isn't an electric or magnetic field, the smart fluid is Newtonian-like. When there is an application of a suitable field, the particle forms chains that causes a yield stress to develop. This yield stress must be overcome before flow can occur[11].

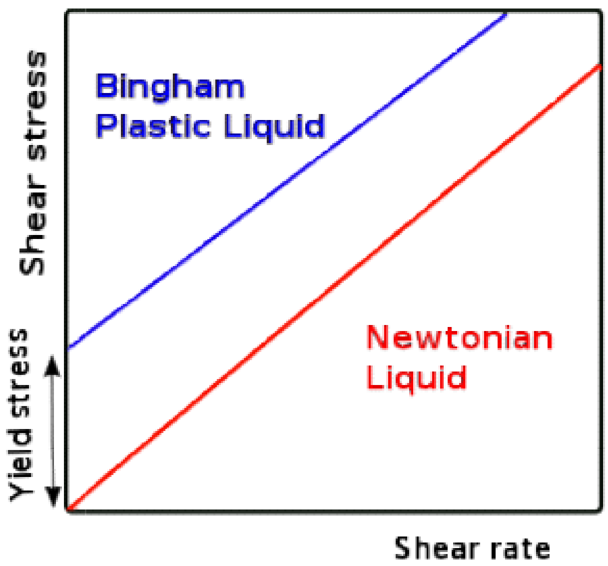

Figure 2. Shear stress vs shear rate for Newtonian fluid and Bingham plastic.

[10] https://pdfs.semanticscholar.org/d14e/ef9424e34a108fc9b0dc1610004f51100b56.pdf
[11] Tibor Medvegy: Investigation of smart fluid properties, University of Pannonia, Institute of Physics and Mechatronics, Hungary

Two regimes are defined:

- pre-yield, where the yield stress τ_b is below the curve and thus fluid flow does not occur;
- post-yield, where τ_b is exceeded and consequently flow occurs.

ER fluids has a maximum value of yield stress $\tau_b$typically within the range 3 – 5 kPa. MR fluids, indeed, has a dynamic yield strength of 100 kPa[12].

Furthermore, modern MR fluids will typically operate from 240 to 150°C, while ER fluids operates within the temperature range from 15 to 90°C. The electrical source required to excite the fluid is:

- up to 10 kV for ER fluids;
- 12 V for MR fluids.

Between ER and MR fluids, the second has the best quality to be commercialized and used for future devices.

4. Operating Modes

Smart fluids can operate with three operating modes[13][14]:

- First – flow/valve mode: smart fluids are free to flow between a pair of stationary electrodes or poles (ER or MR). The physic proprieties of the fluid are controlled by varying the electric or magnetic field across the electrodes or poles;
- Second – shear mode: it is allowed the relative motion, either rotational or translational, at 90° to the direction of the applied field. In this way the smart fluid is placed in shear. This is the mode at the basis of a variety of engineering devices, because the shear stress/shear rate characteristics can be controlled continuously through the applied field;
- Third – squeeze flow modes: the electrodes (or poles) are free to translate in a parallel direction of the applied field. The smart fluid is subjected to alternate compression or tension. The displacements of the electrodes are small (few millimeters), anyway large forces are available from compact devices.

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[12] j. d. carlson: in 'Adaptronics and smart structures', (ed. H. Janocha), 180 – 195; 1999, Springer-Verlag
[13] https://www.slideshare.net/MDNAWAZ3/magneto-rheological-fluid-ppt
[14] https://www.researchgate.net/publication/224862135_Magnetorheological_fluids_a_review_Soft_Matter_73701-3710/figures?lo=1

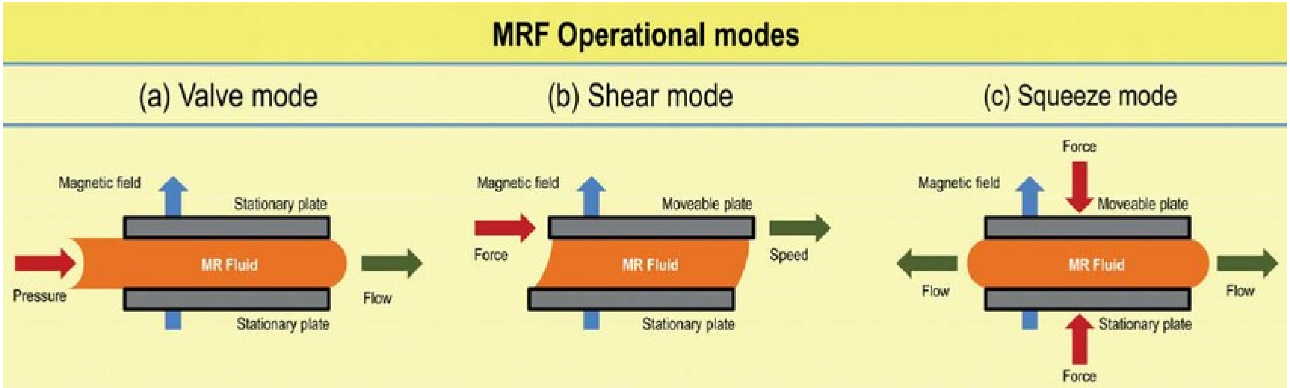

Figure 3. Operating Modes.

5. Application

The propriety of smart fluids described above has allowed broad-based research and development of many different systems including vehicle dampers, intelligent hydraulic systems, vibration control mounts, and smart robots.

In the following, there is a list of some current and future smart fluids applications:

- Semi-active shock absorbers, utilizing MR fluid as the working fluid, have been successfully implemented on some vehicle companies including Cadillac and Ferrari[15];
- ER dampers operating in the squeeze-flow mode[16];
- Smart fluids used for organic, inorganic or hybrid devices in the liquid state, kept in a fixed volume by surface tension or by a confining membrane that protects them from a harsh environment, used to do autonomous robotic systems with unique capabilities, biologically inspired[17];
- Vibration isolators to isolate the vibration sources from one to the parts by install vibration isolator between them[18];
- In the civil engineering field, the use of smart fluid dampers for isolating buildings from seismic disturbances[19];

[15] http://journals.sagepub.com/doi/pdf/10.1155/2014/254864
[16] a. k. el wahed, j. l. sproston and r. stanway: J. Intell. Mater. Syst. Struct., 2002, 13, 655 – 660
[17] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5515117/
[18] http://ro.uow.edu.au/cgi/viewcontent.cgi?article=4143&context=eispapers
[19] Li Y, Li J, Tian T, Li W 2013 A highly adjustable magnetorheological elastomer base isolator for applications of real-time adaptive control Smart Mater. Struct. 22 095020.

- B.-K. Song et al. proposed to use MR fluids for a new type of 4-degree of-freedom haptic master which is applicable to a robot-assisted minimally invasive surgery system[20];

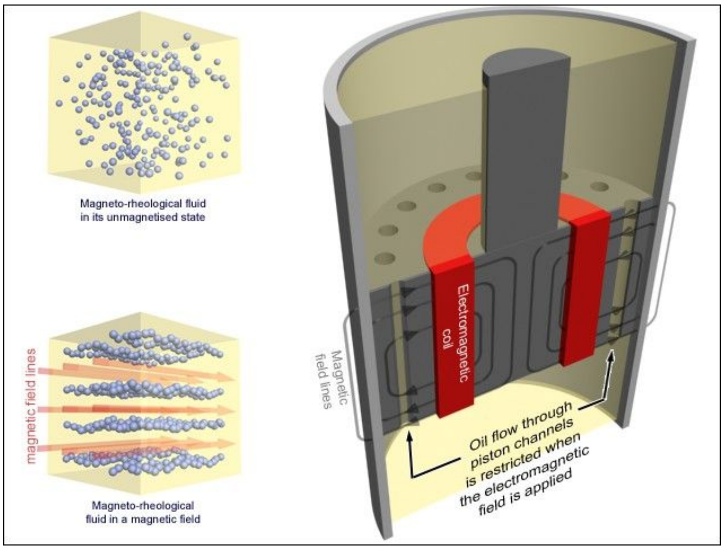

Figure 4. Smart Fluid Damper.

6. Conclusion

In this paper the proprieties of smart fluids, dividing it in ER and MR fluids are described. The macroscopic model of this kind of technology is analyzed, focusing on smart fluids propriety variations. The operate modes are described too, with a conclusion on applications of smart fluids.

Understanding the strong potentiality of smart fluid devices is critical to their future development and applications. A challenge task is to provide strong and uniform magnetic field to the material, considering the low permeability of MR elastomer. However, research has been mainly focused on the frequency shifting capacity of the devices, such as for vibration absorbers and vibration isolators. Another challenge is to develop appropriate control strategies for the various applications.

[20] http://iopscience.iop.org/article/10.1088/1361-665X/aabc2e