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MAGNETO-RHEOLOGICAL FLUID (MRF) AND ELECTRO-RHEOLOGICAL FLUID (ERF) DEVICE MODELING

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Abstract
Magneto-rheological fluids (MRF) and electro-rheological fluids (ERF) are smart, synthetic fluids, changing their viscosity from liquid to semi-solid state, if a magnetic or an electric field is applied. This paper treats the rheological properties of fluids and discusses various phenomenological models for rheological fluid devices. MRF and ERF have attracted considerable interest due to their wide range of use in vibration dampers for semi-active vehicle suspension systems, machinery mounts or seismic protection of structures; their damping capabilities can be very quickly adjusted by applying a variable magnetic or electric field. The advantages and disadvantages concerning the using in applications of MRF and ERF are presented in [2], [4].
Keywords: magneto-rheological fluid, electro-rheological fluid, modeling

1. Introduction

The aim of the paper is the description of properties of the two kinds of fluids and the presentation of some phenomenological models for rheological fluids like:

- parametric models: Bingham model, extended Bingham model, three element model (Powell 1994), BingMax model, Bouc-Wen model, modified Bouc-Wen model, non-linear viscoelastic-plastic model (Kamath and Wereley 1997);
- non-parametric models: Chebyshev polynomial fit, neural networks.

2. Phenomenological Models

Most often, the considered devices operate in the valve (flow) mode, the direct shear mode or a combination of the two modes, as it is shown in figure 1.

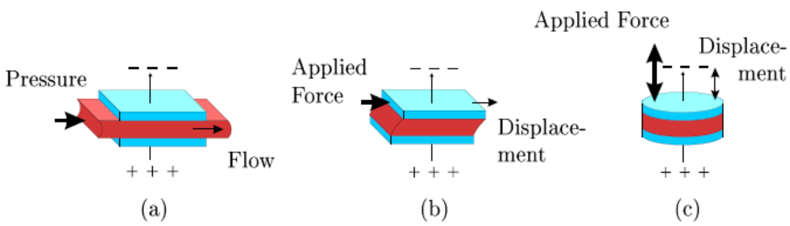


Figure 1: *Basic operating modes of rheological fluid devices (a) Valve mode. (b) Direct shear mode. (c) Squeeze-flow mode*

It is useful to distinguish between models which qualitatively simulate the rheological response and are fitted to experimental result by adjusting few parameters (parametric models) and models which are entirely based on the performance of a specific fluid device (non-parametric models) [5].

3. Parametric Models

3.1. Bingham Model

The Bingham model [8] behaves as a solid until a minimum yield stress τ_y is exceeded and then exhibits a linear relation between the stress and the rate of shear of deformation. The shear stress τ developed in fluid is

$$\tau = \tau_y \cdot \mathrm{sgn}(\dot{\gamma}) + \eta\dot{\gamma}, \qquad (1)$$

where $\dot{\gamma}$ is the (shear) strain rate and η is the plastic viscosity of the fluid, i.e. the (Newtonian) viscosity at zero field.

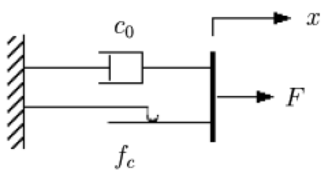


Figure 2: *Bingham model*

In figure 2 it is shown the mechanical model with Coulomb friction element in parallel. The force F generated by the device is

$$F = f_c \cdot \mathrm{sgn}(\dot{x}) + c_0\dot{x}, \qquad (2)$$

where $\dot{x}$ denotes the velocity attributed to the external excitation, and the damping coefficient c_0 and the friction force f_c are related to the fluid's viscosity and the filed dependent yield stress, respectively.

3.2. Extended Bingham Model

This viscoelastic-plastic model [1] consists of the Bingham model, in series with the three-parameter element of a linear solid (Zener element), as shown in figure 3.

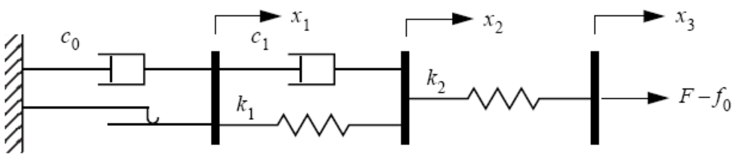


***Figure 3**: Extended Bigham model*

The force in this system is given by

$$F = \begin{cases} c_0\dot{x}_1 = f_c \,\mathrm{sgn}(\dot{x}_1) \\ k_1(x_2 - x_1) + c_1(\dot{x}_2 - \dot{x}_1), & |F| > f_c \\ k_2(x_3 - x_2) \\ \\ k_1(x_2 - x_1) + c_1\dot{x}_2, & |F| \le f_c \\ k_2(x_3 - x_2) \end{cases},$$

(3)

where the field dependent parameters c_1, k_1 and k_2 are associated with the fluid's elastic properties in the pre-yield region.

3.3. Three Element Model (Powell 1994)

This model consists of a viscous damper, a non-linear spring and a frictional element in parallel (figure 4).

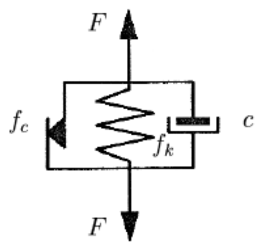


***Figure 4:** Three element model (Powell 1994)*

The Coulomb friction force f_c is modeled with static and dynamic friction coefficients f_{cs} and f_{cd}, respectively. There are also introduced the smoothing functions for the friction force, instead of the signum function,

$$f_c = \begin{cases} f_{cs}\left(1 + \frac{f_{cd}}{f_{ce}} e^{-a|\dot{z}|}\right)\tanh(e\dot{z}), & \dot{z}\cdot\ddot{z} \geq 0 \\ f_{cd}\left(1 - e^{-b|\dot{z}|}\right)\tanh(e\dot{z}), & \dot{z}\cdot\ddot{z} < 0 \end{cases} \qquad (4)$$

where z is the displacement transmitted to the rheological device and $\dot{z}$ and $\ddot{z}$ denote the corresponding velocity and acceleration, respectively.

The force generated by the device is given by $F = f_c + f_k + c\dot{z}$, (5)

were $f_k = k\tanh(dz)$ is the nonlinear force of a softening spring.

3.4. BingMax Model

This model consists of a Maxwell element in parallel with a Coulomb friction element, figure 5. The force in this system is given by

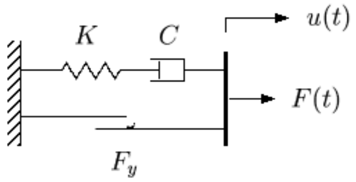


Figure 5: *BingMax model*

$$F(t) = K\int_0^t e^{-\frac{t-\tau}{\lambda}}\dot{u}(\tau)d\tau + F_y\,\mathrm{sgn}[\dot{u}(t)], \qquad (6)$$

where $\lambda = \frac{C}{K}$ is the quotient of the damping constant *C* and the spring stiffness *K*, and F_y denotes the permanent friction force.

3.5. Bouc-Wen Model

The mechanical model Bouc-Wen is shown in figure 6.

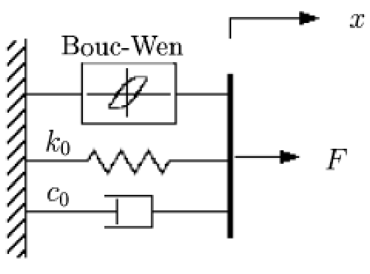


Figure 6: *Bouc-Wen model*

The force generated by the device is given by

$$F = c_0\dot{x} = k_0(x - x_0) + \alpha z\,, \tag{7}$$

where the hysteretic component z satisfies

$$\dot{z} = -\gamma|\dot{x}|z|z|^{n-1} - \beta\dot{x}|z|^n + \delta\dot{x}\,. \tag{8}$$

By adjusting the parameter values α, β, γ, δ and n, it is possible to control the force-velocity characteristic.

3.6. Modified Bouc-Wen Model

The structure of the model is shown in the figure 7. The equation for the force in this system is given by $F = \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0) = c_1\dot{y} + k_1(x - x_0)$. (9)

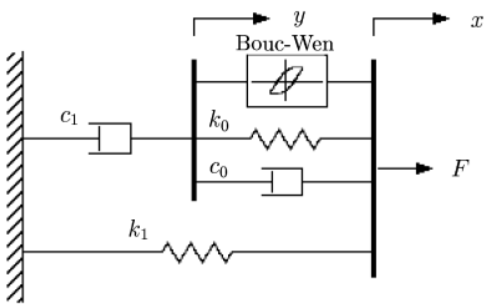
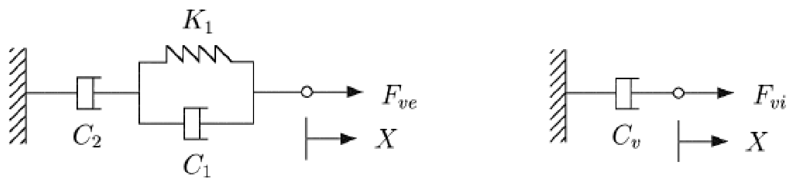


Figure 7: *Modified Bouc-Wen model*

3.7. Non-Linear Viscoelastic-Plastic Model (Kamath and Wereley 1997)

This model combines two linear shear flow mechanisms with non-linear weighting functions, figure 8.



(a) Viscoelastic mechanism *(b)Viscous mechanism*

Figure 8: *Viscoelastic-plastic model (Kamath and Wereley 1997)*

4. Non-Parametric Models

The non-parametric models are based on device performance alone. They usually require a large amount of experimental data showing the fluid response to different loads under different operational conditions (Jung et al. 2004). Proposed models in this category are based on Chebyshev polynomials (Ergott and Masri 1992, Gavin et al. 1996), neural-networks (Chang and Roschke 1998, Zang and Roschke 1998, Wang and Liao 2001), neuro-fuzzy system (Schurter and Roschke 2000) or wavelet-based identification technique (Jin et al. 2001, Jin et al. 2002), for example.

4.1. Chebyshev Polynomial Fit

In order to characterize the behavior of this model [5], the restoring force F of the rheological device is predicted by an analytical function $\hat{F}$, constructed by two-dimensional orthogonal Chebyshev polynomials

$$F(x, \dot{x}) \approx \hat{F}(x, \dot{x}) = \sum_{i,j=0}^{m} C_{ij} T_i(x') T_j(\dot{x}') , \tag{14}$$

where the $C_{ij} \in \mathbf{R}$ denote the two--dimensional Chebyshev coefficients and m is the degree of polynomial. The values x' and $\dot{x}'$ are obtained by normalizing the displacement x and the velocity $\dot{x}$ that are associated with the external excitation to the interval $[-1,+1]$.

4.2. Neural Networks

The neural networks [5] consist of several processing units (neurons), whose inputs are weighted and passed to an activation (signal) function, producing one single output. The weighting depends on the strength of the neurons' interconnection and can be adjusted by a learning process.

The researches have shown that the performances of the neural network are surpassed by the discrete element models, such the Bingham model.

5. Conclusions

Concerning the vibration attenuators, as future directions of study it is suggested the elaboration of some models that could take into account the influence of the gas accumulator, attached to the damper, the modifications induced by the temperature increase during the work, as well as the behavior at high accelerations.

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