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RESONANCE RESPONSE OF ELECTRORHEOLOGICAL FLUIDS IN VERTICAL OSCILLATION SQUEEZE FLOW*

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The resonance effect of microcrystalline cellulose/castor oil electrorheological (ER) suspensions was studied in a compressed oscillatory squeeze flow under external electric fields. The resonance frequency first increases linearly with increasing external field, and then shift to high-field plateau. The amplitudes of resonance peak increase sharply with the applied fields in the range of 0.17–1.67 kV/mm. The phase difference of the reduced displacement relative to the excitation force inverses in the case of resonance. A viscoelasticity model of the ER suspensions, which offers both the equivalent stiffness and the viscous damping, should be responsible for the appearance of resonance. The influence of the electric field on the resonance frequency and the resonance hump is consistent qualitatively with the interpretation of our proposed model. Storage modulus G' was presented for the purpose of investigating this influence.

Keywords: Electrorheological Fluids, Resonance Response, Squeeze Flow
PACC: 8350, 8380, 6230

I. INTRODUCTION

Electrorheological (ER) suspensions exhibit remarkable changes in structure and apparent viscosity when subjected to an external electric field exceeding a critical value. Important physical insight into ER effect was provided by electrostatic polarization mechanism, which explains most experimental observations such as nonzero shear modulus and yield stress. Field- induced polarization of the dispersed particles relative to the continuous phase produces dipole- dipole interparticle force that results in forming particle chains, columns, and more complicated fibrous structures observed in experiments[1−2]. Together with the particle structure formation, the apparent viscosity, which is defined as the ratio of shear stress over shear rate, increases by a few orders of magnitude. For instance, the shear stress may reach up to 10kPa at shear rate of $28\,s^{-1}$ and dc electric field strength of 2 kV/mm for complex strontium titanate suspensions[3]. Applications of stress transfer by electric control can benefit many devices such as active shock absorbers and engine mounts, clutches and brakes, actuators, control valves and artificial joints[4]. Recently, in addition to normally considered shear flow, potential applications in squeeze flow, in which the fluid is subjected to tension and compression also have attracted attention[5−8]. It is suggested that ER fluids in squeeze flow could be more effective especially in vibration control of engine mounts or other limited-travel devices[8]. Yield stresses provided by ER fluids in squeeze flow are of a magnitude that is sufficient to control resonant magnification and high frequency isolation in simple and compact damping devices. Sproston *et al.* described the stress developed in squeeze flow employing the models that account for the pressure gradients arising from viscous flow and the appearance of yield phenomena[9−11]. They studied experimentally and theoretically the characteristics of ER fluids and their applications to vibration control when used in squeeze flow. The stable state and dynamic characteristics of ER fluids in squeeze flow were explored through theoretical models and microstructure computer simulation. For example, the tensile and compressive behaviors were investigated and rheopectic effect of ER fluids under compressive loading was qualitatively explained using the electrostatic model and Hertzian contact theory[12]. Using computer simulation, the mechanical properties of ER fluids under shear, compressive and elongation loading

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conditions have been studied[13−14]. The simulation results showed that electrorheological fluids under compressive loading transmit the largest force from one plate to another. In this paper, we concentrate on the field-induced resonance effect observed in ER fluids under squeeze flow based on microcrystalline cellulose/castor suspensions. Damping device design needs consideration of resonance within the operating range of the machinery. Understanding the physical origin of resonance and knowledge of how various parameters influence the vibratory response will contribute to optimizing the performance of the vibration device. Therefore, we further investigated the influence of the electric field on the resonance in scanning oscillatory frequency from 5 to 50Hz. In our experimental tests, the value of electric field strength is approximately the field strength where the lower electrode locates at the equilibrium position over the displacement cycle. The change in the field strength is insignificant when the change of strain magnitudes range from 10^{-5} to 10^{-2}.

Ⅱ. EXPERIMENTS

The ER sample consists of dried microcrystalline cellulose powder with size ranging from 30 to 60 μm, which is dispersed in castor oil with solid phase volume fraction of 25%. The shear stress of the suspensions is 2.1 kPa at shear rate 50 s^{-1} under electric field of 3.2 kV/mm.

The ER sample is sandwiched with two parallel disk electrodes of diameter 60 mm and a gap of 3mm (illustrated in figure 1). The upper electrode that attaches to a piezoelectric force sensor is held motionless .The lower one is stuck to a recessed cylindrical cavity of inner diameter 80mm. Another identical sensor links rigidly the cavity and an electromagnetic vibrator, which produces vertical sinusoidal oscillatory motion with frequencies from 5 to 50 Hz. A displacement sensor is used to measure the moving amplitude of the lower electrode.

Two sets of model SR785 Channel Dynamic Signal Analyzers (Stanford Research Systems, Inc.), whose measurement groups include FFT, sweep + sine and time/histogram, etc., measure and analyze vibrations with linear spectrum, frequency response and cross spectrum. In addition, the SR785 also provides a sinusoidal source signal to control the electromagnetic vibrator, which can offer a maximum exciting force above 50N through a power amplifier. In experiments, measurement channels of the input force and the excitation force can be changed through the scanner. The apparatus was adjusted to keep very small strain magnitudes before each measurement to guarantee the system working in a linear regime.

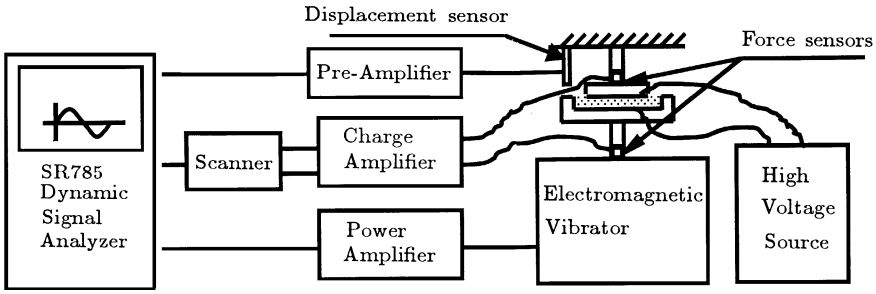


Fig.1. Experimental arrangement. The shaded part represents ER suspension.

Ⅲ. RESULTS AND DISCUSSIONS

In figure 2, the reduced displacement, which is defined as the ratio of the oscillatory displacement to the amplitude of excitation force, is plotted as a function of the oscillatory frequency at different external electric field. In the absence of external electric field, owing to the Newtonian-fluid characteristics of the suspension, the reduced displacement is significantly larger than those in the presence of field. In this case, the amplitude decreases with rising oscillatory frequency because there is no sufficient time for the system to respond to the high oscillatory frequency. When the external electric field is applied, the reduced displacement corresponding to the same frequency starts to decrease due to the increment of apparent viscosity. The strain amplitude is less than 10^{-4} under an electric field of 0.33 kV/mm. A peak becomes distinguishable when the field exceeds 0.17 kV/mm, and the peak corresponding to 29.5 Hz of oscillatory frequency becomes obvious when the field

reaches 0.33 kV/mm. However, no such phenomenon occurs in the absence of external electric field. We refer to the peak as the resonance peak. With increasing field, it can be seen that the resonance humps become steeper. From figure 2(b), the phase angle of amplitude relative to excitation force is about $\pi/2$ when resonance occurs. This is a general standard of vertifying resonance in industrial application. When the field strength is over 0.67 kV/mm, the phase generates inversion within the resonance region. However, no obvious phase change is observed in the zero-field curve. Beyond the resonance region, the reduced displacements still decrease with the field rising and will merge into a single curve at still higher field. There is an extra peak or shoulder for each curve around 33 to 34 Hz in figure 2(a). It is unlikely that these peaks or shoulders relate to ER effect as it appears also in the absence of electric field (curve 0). The reason of a small peak that appears in curve 1 (E=0.33 kV/mm) at 27.5 Hz is not clear either.

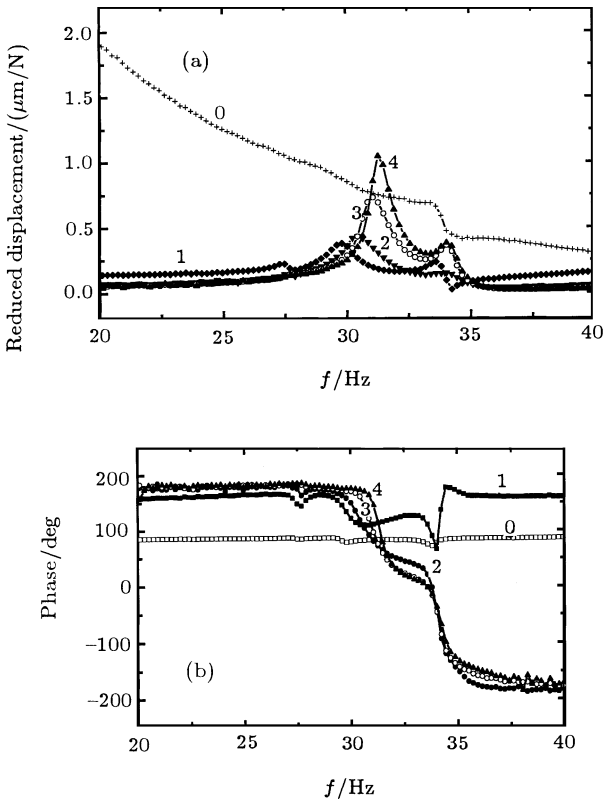


Fig.2. The reduced displacement (a) and phase (b) of microcryatalline cellulose versus oscillatory frequency. 0, 1, 2, 3 and 4 represent electric fields of 0, 0.33, 0.67, 1.00 and 1.33 kV/mm, respectively.

The frequencies corresponding to the resonance peak under different applied fields are shown in figure 3. The resonance peak shifts to higher frequencies with increasing electric field. There is a linear relationship between the resonance frequency and the applied field at low fields. The growth of frequency slows down and reaches a plateau at higher fields.

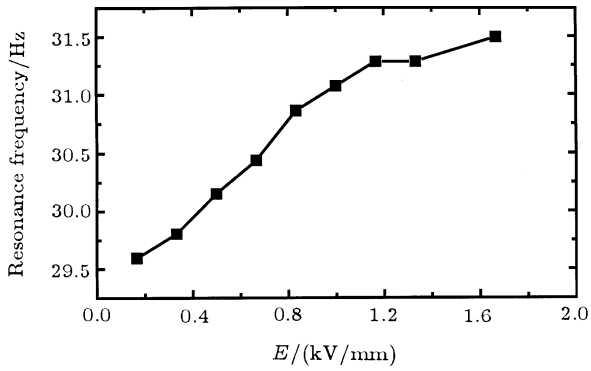


Fig.3. The shift of resonance frequency with external field from linear growth at low field to high-field plateau.

Figure 4 plots the relationship between the resonance peak values and the external fields. The resonance hump increases faster than linearly with external fields. A curve of exponential growth fit is also presented. No plateau was found at the high electric field within our experimental range.

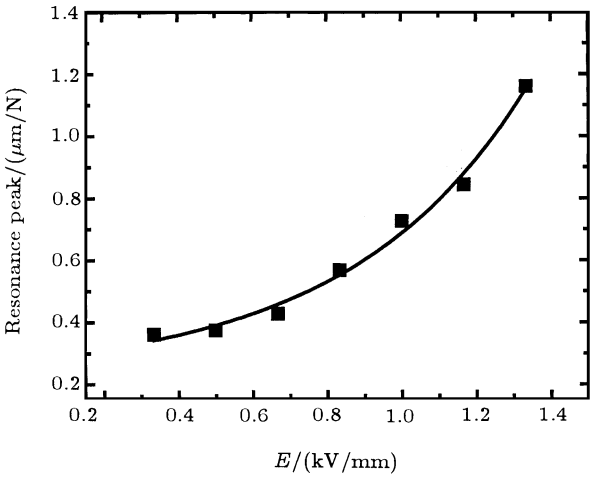


Fig.4. Relationship between the height resonance hump and the field. The solid curve is an exponential growth fit of the data points.

In consideration of the fact that ER fluids often behave as viscoelastic materials, a simple model (figure 5) can be used for the interpretation of the experimental results when an ER fluid is regarded as a Kelvin viscoelastic medium.

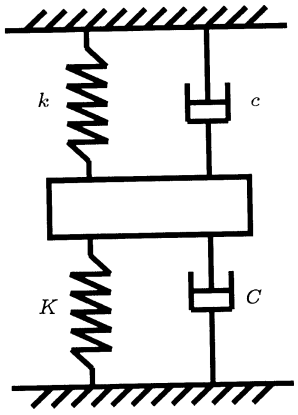


Fig.5. Schematic diagram of the viscoelasticity model.

Here, m is the mass of the vibrating part of the system including ER suspension, the cavity and the moving part of electromagnetic vibrator. m is equal to 0.536 kg. K_0 and C_0 are the elastic and damping factors of the vibrator, respectively. K_0 is about 12290(N/m). k and c are the equivalent elastic factor and damping factor of ER suspensions, respectively, which reflect the elastic and viscous characteristics, and can vary with electric field. In this mode, ER fluids offer both the viscous damping and the equivalent rigidity. According to the proposed mechanisms of the ER response, the dependence of material viscoelasticity on the electric field is determined by interparticle interactions including electrostatic force, hydrodynamic force and short-rang repulsive force, etc. The electrostatic interactions induced by the external electric field causes the particles to aggregate into columnar structure that spans the two electrodes. Viscoelasticity arises from the electrostatic interaction between particles within these structures. In this model, we attribute the appearance of the resonance to the result of the synergistic effect of the ER suspension and the vibration component. For very small strain amplitudes, the motion of m is given by the following equation:

$$m\frac{\mathrm{d}^2x}{\mathrm{d}t^2} + (k+K_0)x + (c+C_0)\frac{\mathrm{d}x}{\mathrm{d}t} = F_0\sin\omega t \quad (1)$$

Under the condition that the initial displacement and initial velocity are zero, the resonance frequency and the reduced displacement of the resonance can be deduced on the base of the resonance theory:

$$f = \frac{1}{2\pi}\left(\frac{k+k_0}{m}\right)^{1/2}, \quad (2)$$

and

$$\frac{x_{\max}}{F} \cong \frac{1}{2\pi f(c+c_0)}, \quad (3)$$

where f is the resonance frequency, $x_{\max}$, is the maximum resonance amplitude, and F the amplitude of excitation force.

Since the increment of the particle interactions is a factor leading to the growth of the elastic coefficient with increasing electric field strength, the resonance frequency will shift to a higher value with electric field according to equation 2. This can be understood more clearly from the results of the strain sweep experiments performed on this sample at different electric field strengths at the oscillatory frequency of 12 Hz (see figure 6).

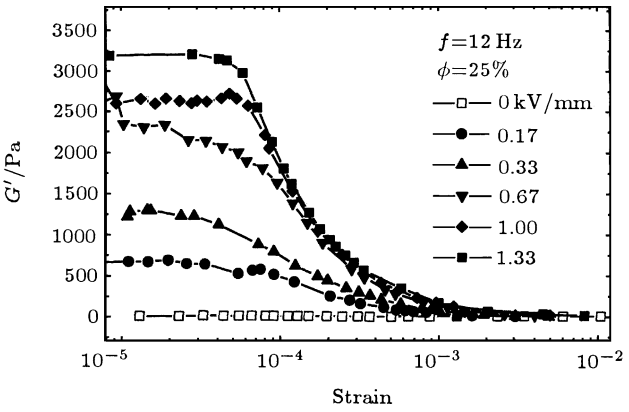


Fig.6. The dependence of storage modulus G' on the electric fields and the strain amplitudes.

According to the linear viscoelasticity theory, storage modulus G' should be independent of strain amplitude and stress. At high electric field, linear viscoelastic behavior is observed only for very small strain amplitudes (less than 10^{-4} in figure 6). G' then falls into a single curve which has "fluid" characteristics for large strain amplitudes. G' increases with field strength when the strain is not more than 10^{-3}. G' is proportional to the equivalent stiffness, satisfying the relation of $k = G' \times (s/d)$. Here s is the area of the electrode, which is equal to 2.83×10^{-3} m^2 and d, the gap between two electrodes, is 3mm. Storage modulus relates to the elasticity parameter k out of resonance region. Substituting experimental data of storage modulus to equations 1 and 2 gives the range of resonance frequencies. From this model, the resonance frequencies should appear in the range of 24Hz to 32Hz when G' rises from zero to 10^4 Pa. This agrees with the data in figure 2a in the order of magnitude.

In the case of resonance, the increment of the strain amplitude causes ER suspensions to flow. Under a squeeze flow, the particle aggregation along field direction as the field increases leads to a reduction of flow resistance that produces damping. Therefore, in

consideration of equation 3, we can attribute the sharp growth of the resonance peak with electric field to the decrease of damping factor.

IV. CONCLUSIONS

The resonance effect comes from the change of the viscoelasticity of microcrystalline cellulose/castor oil suspensions under external electric field. The hydrodynamic resistance is significant in absence of electric field, so the resonance effect arises only when the equivalent stiffness dominates over the viscosity damping as the electric field increases. Resonance peak value and resonance frequency can be adjusted through the electric field. It is necessary to further study the relations between viscoelasticity and microstructure of ER suspensions in squeeze flow.

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