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The electric field and frequency responses of giant electrorheological fluids*

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The giant electrorheological (ER) fluid is based on the principle of a polar molecule dominated electrorheological (PM-ER) effect. The response of the shear stress for PM-ER fluid in alternate electric fields with triangle/square wave forms for different frequencies has been studied. The results show that the shear stress cannot well follow the rapid change of electric field and the average shear stresses of PM-ER fluids decrease with the increasing frequency of the applied field due to the response decay of the shear stress on applied field. The behavior is quite different from that of traditional ER fluids. However, the average shear stress of PM-ER fluid in a square wave electric field of $\pm E$ at low frequency can keep at high value. The obtained knowledge must be helpful for the design and operation of PM-ER fluids in the applications.

Keywords: electrorheological fluid, frequency response

PACS: 83.80.Gv, 83.85.Cg, 83.85.Jn, 83.60.Np **DOI:** 10.1088/1674-1056/27/7/078301

1. Introduction

How can the electrorheological (ER) fluids be applied in practical technology still is a major concern. The basic issue is to adjust the electric field for controlling the shear stress of ER fluid and then operate the mechanical action. In such operations, not only high enough shear stress of ER fluid is needed, but also the characteristics of the electrical response and frequency dependence of ER fluid should be realized. In traditional (dielectric) ER fluids consisting of dielectric particles and insulating liquids, the ER effect originates from the dielectric interaction of suspended particles in an electric field E. In such ER fluids, the response of shear stress to the electric field has been well understood.[1–5] It was found that with the frequency increase of the applied AC electric field the shear stress may either increase[1,6,7] or decrease,[7–9] determined by the competition between the dielectric and the conductive properties of particles and liquids in the suspensions. However, in the giant ER fluids,[10] which are based on the principle of a polar molecule dominated electrorheological (PM-ER) effect,[11,12] the shear stress is orders of magnitude higher than that of the conventional ER fluids under applied DC electric field. It has been noticed that the shear stress of PM-ER fluids cannot well follow the rapid change of the electric field in an AC field, not as the same as that in traditional ER fluid. By measuring the frequency dependence of PM-ER fluids in AC sinusoidal fields, the average shear stress always decreases with the increase of the field frequency. The results indicate that the PM-ER fluids are not suitable for the applications under the sinusoidal field generated by commercial AC electric powers. In practice, however, for controlling the ER action, the electric wave shape of triangle or square form with slow or fast changing rate is commonly applied. It is needed to know how the shear stress follows the triangle and square wave fields at different frequencies.

In this paper, the electric response and frequency dependence of PM-ER fluids have been studied under triangle and square wave electric fields. The measured results show that at low frequencies, the shear stress can follow the change of the field strength and keeps a similar wave shape, while shape distortion of the shear stress becomes more serious as the frequency increases. The average amplitude of the shear stress in a period decreases with increasing frequency due to response decay. In a square wave electric field with $\pm E$ at low frequency, however, we find that the average shear stress of the PM-ER fluid still can keep the same value as that in DC field. This may take advantage in the applications for PM-ER fluids.

2. Experiment

The PM-ER fluids studied were Ca–Ti–O complex (CTO) particles mixed with hydraulic oil and ground in an agate ball mill with volume fraction of 39%. The CTO particles were prepared by the co-precipitation method. The detailed processing and the compositions of the CTO particles were described in previous publications.[13–15] The average size of the CTO particles was ~ 50 nm and the density was 2.078 g/cm^3 measured by using gas pycnometer (AccuPyc II 1340, Mi-

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cromeritics).

The frequency response measurements were performed with a home-made system.[13–15] The sample was sufficiently stirred before each measurement to ensure that it kept a homogeneous state. The responses of shear stresses under alternate electric fields with triangle and square wave forms for different frequency f were measured respectively at shear rate of 50 s^{-1}. The data collections were performed with sampling rate of 4k per second. The shear stress $\tau(t)$ varying with the electric field in time sequence were obtained at various frequencies in three cases: (i) triangle wave electric field with a varying strength between $-E_{max}$ and $+E_{max}$, (ii) square wave electric field with only positive pulses (from 0 to $+E_{max}$), and (iii) square wave electric field in between $-E_{max}$ and $+E_{max}$. All the measurements were performed at room temperature.

3. Results and discussion

3.1. The response of shear stress in triangle wave field

The electric field response of shear stress $\tau(t)$ of the PM-ER fluids in a triangle wave electric field $E(t)$ with peak

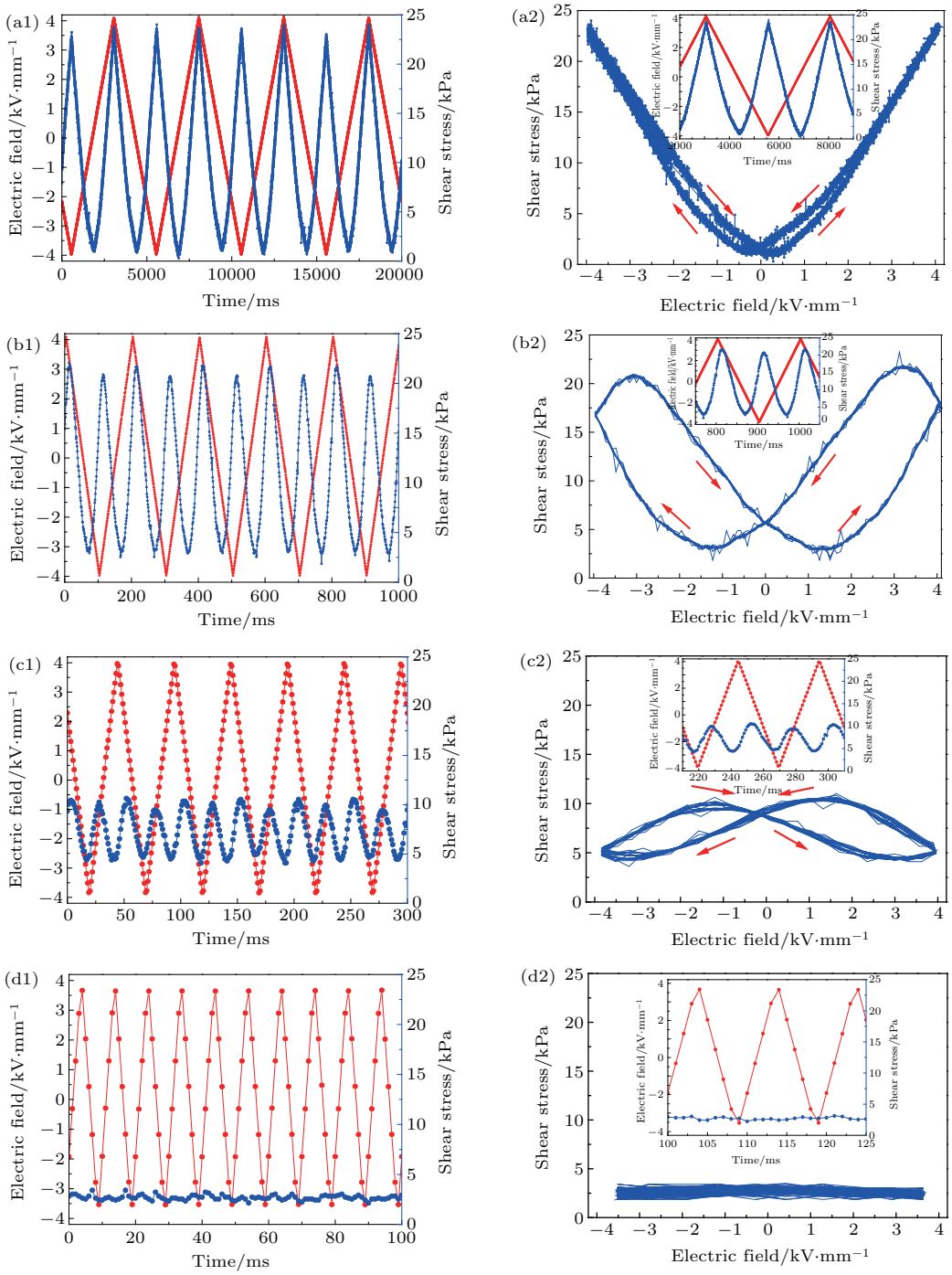


Fig. 1. (color online) Selected curves of $\tau(t)$ (blue) varying with time under triangle electric field $E(t)$ in between −4 kV/mm and +4 kV/mm (red) of (a) $f = 0.2$ Hz, (b) $f = 5$ Hz, (c) $f = 20$ Hz, and (d) $f = 100$ Hz for CTO based PM-ER fluid (left column). Right column shows the corresponding relations of shear stress versus field strength for all measured curves. Insets show the enlarged curve of $\tau(t)$ versus $E(t)$ of triangle wave.

strengths of ±4 kV/mm was measured in a frequency range from $f = 0.2$ Hz to 100 Hz. Selected response curves of $\tau(t)$ to $E(t)$ at $f = 0.2$ Hz, 5 Hz, 20 Hz, and 100 Hz are shown in left column of Fig. 1. Correspondingly, the relations of τ and E for all periods of $E(t)$ at those frequencies are mapped out and shown in the right column of Fig. 1. Enlarged curves of $\tau(t)$ versus $E(t)$ are also shown in the right column as insets. It can be seen that the shear stress in the plots of τ–E are separated into two loops in the sides of positive and negative electric fields with symmetrical patterns, because of the equal response of shear stress on both positive and negative fields. Figure 1(a) shows that the maximum magnitude of the shear stress can reach up to about 24 kPa and the $\tau(t)$ curve can basically follow $E(t)$ with a triangle shape quite well when $f = 0.2$ Hz. It is easy to take for granted that the maximum magnitude of $\tau(t)$ should be at $E(t) = -E_{\max}$ and $E(t) = +E_{\max}$ and the minimum at $E(t) = 0$. However, as shown in Fig. 1, when the frequency increases, the shear stress of ER fluid cannot well follow the change of electric field and even the shape seriously deviates from the field waveform. As seen in right column of Fig. 1, the relation of τ and E is totally different from the expected shape as the frequency is higher. The values of the shear stresses no longer correspond to that of the electric fields respectively. There are obvious shifts between τ and E curves and a dramatic decline of τ value occurs at high frequencies. The maxima of τ appear at about $E = \pm 3$ kV/mm and $E = \pm 1.5$ kV/mm respectively in the field of $f = 5$ Hz and $f = 20$ Hz, for example, while the minima of τ do not correspond to the position of $E = 0$. Furthermore, the values of τ in the field of $f = 100$ Hz even do not vary with E and stay at a low level of 2.5 kPa.

The maximum and minimum values of shear stresses varying with the frequency of the field are plotted in Fig. 2, where the shear stresses and the electric field do not synchronize each other. It is observed that the maximum values of shear stress constantly decrease with increasing frequency and even lose the effect to response the electric field changing at a high frequency triangle field, $f = 100$ Hz for instance.

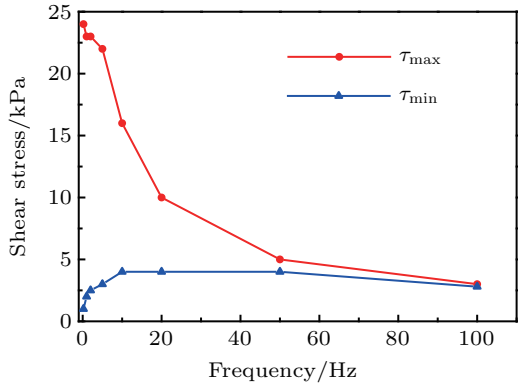


Fig. 2. (color online) The maxima τ_{max} and minima τ_{min} of shear stress in ±4 kV/mm triangle electric field varying with the frequency measured at shear rate of 50 s^{-1} for CTO based PM-ER fluid.

These phenomena come from the response decay of shear stress on E in PM-ER fluids, similar to that in sinusoidal electric fields.[5] Both the orientation of the polar molecules in between the particles and alignment of the particles in PM-ER process need time to reform structures to sustain the shear stress.[11,12] The structural readjustment causes the response delay of shear stress related to the field and emerges the phase shifts between $\tau(t)$ and $E(t)$, and the affects become more serious as rapidly changing the field strength, i.e. increasing the frequency of the field.

3.2. The response of shear stress in square wave electric field (from 0 to $+E$)

The responses of shear stress to the field strength in square waveform with different frequencies were also measured. Some selected response curves of τ versus E at $f =$ 0.5 Hz, 2 Hz, 5 Hz, 20 Hz, and 100 Hz are shown in Fig. 3, where E is from 0 to +4 kV/mm and the duty ratio of the pulse is 0.4. It can be seen that the shapes of the shear stresses can well follow the electric field at low frequencies and distort at higher frequencies. The maximum and minimum values of shear stress as shown in Fig. 3(f) exhibit similar tendency as that in the triangle electric field. Again the maxima of τ at $E = 4$ kV/mm decrease with frequency increasing while the minima at $E = 0$ kV/mm increase with frequency due to the response decay of shear stress to the electric field. The maxima and minima of the shear stress trend towards a same low value when frequency is high enough, $f > 100$ Hz in our case. Due to the feature of the square pulse, the observed average values of shear stresses are larger than that in triangle field.

3.3. The response of shear stress in square wave electric field (from $-E$ to $+E$)

The above observations indicate that the shear stress of PM-ER fluid cannot rapidly follow the change of the electric field if the field strength varies very fast. When an alternative square wave electric field from $-E$ to $+E$ is applied, the response of the shear stress must be insensitive at the transformation edges of $-E$ to $+E$. Figure 4(a) shows the measured responses of shear stresses in a square electric field in between −5 kV/mm and +5 kV/mm with $f = 1$ Hz and the width ratio of $-E$ to $+E$ pulses as 6:4. For a comparison, the response in an electric field from 0 to +5 kV/mm with $f = 1$ Hz is shown in Fig. 4(b). It can be seen from Fig. 4(a) that there are some slight drops of shear stress occurred at the transition points from +5 kV/mm or −5 kV/mm to 0 kV/mm. Such small drops on the magnitude of shear stress only lasts in very short time, of which the number is $2f$ per second. The field transforms from +5 kV/mm or −5 kV/mm to 0 kV/mm are very fast, typically about 10 μs. Because of the response delay of the shear stress on the field, the measured magnitude of shear stress can still keep high values in whole time

range when the frequency is not high. The average shear stress shown in Fig. 4(a) is 28.5 kPa, which is almost the same as that at $E_{max} = 5$ kV/mm as shown in Fig. 4(b). As frequency increases, the shear stress drops appear more frequently and cause the average shear stress to decrease more. In our measurements, it is observed that when f is less than about 10 Hz, the average shear stress can still keep a high value and only loss a little compared to that in a DC field.

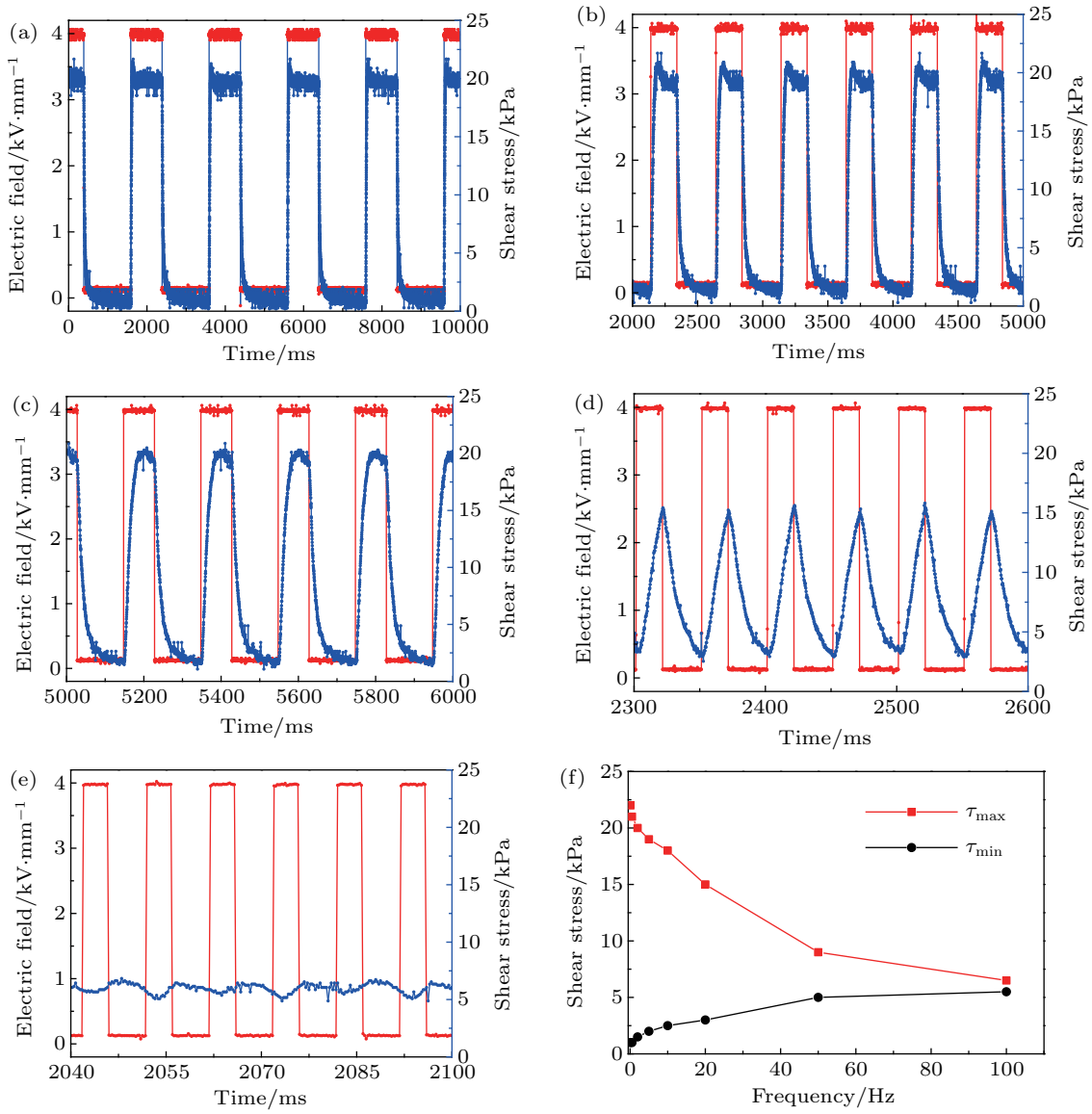


Fig. 3. (color online) Selected curves of shear stress (blue) varying with square electric field (red) at $f =$ (a) 0.5 Hz, (b) 2 Hz, (c) 5 Hz, (d) 20 Hz, and (e) 100 Hz, and (f) the maximum and minimum shear stress in a square electric field varying with the frequency measured at shear rate of 50 s^{-1} for CTO based PM-ER fluid.

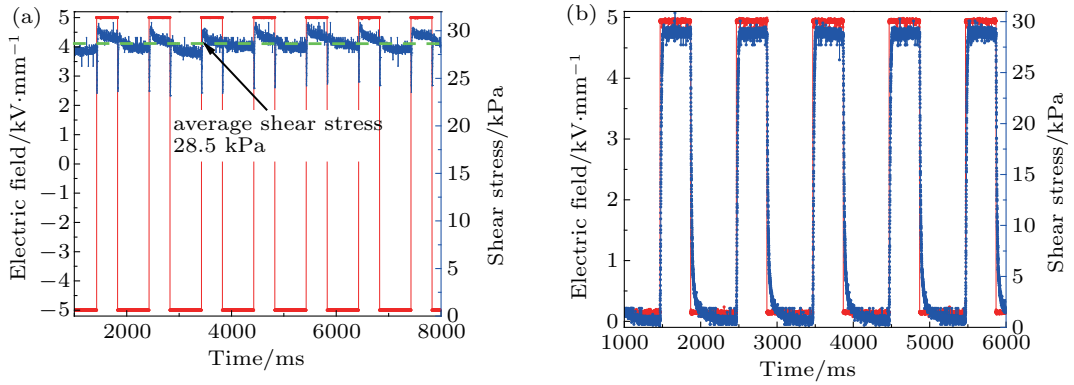


Fig. 4. (color online) (a) The relation of shear stress (blue) and square electric field (red) with $f = 1$ Hz and $E_{max} = \pm 5$ kV/mm. The dashed line indicates the average value of the shear stress. (b) Shear stress (blue) versus positive square electric field (red) with $f = 1$ Hz and $E_{max} = +5$ kV/mm for CTO based PM-ER fluid measured at shear rate of 50 s^{-1}.

In whole frequency region, it is clear that the measured shear stresses by using square wave (Fig. 4(b)) are able to reach higher values comparing to that in triangle wave (Fig. 2). Obviously, this is due to the factor that the field strength for a square wave keeps higher magnitude flat for a half-period. Thus, in the applications of PM-ER fluids with AC field, the square wave should take advantage rather than triangle or sinusoidal wave.

The advantage by using a square wave field with $\pm E$ is to avoid possible deposition of the particles on the surface of electrodes. Usually the particles in ER fluid may carry some electric charges and then the particles will move and adhere to electrodes in an electric field due to the electrophoresis phenomenon. The attached particles may gradually form an accumulation layer on the surface of electrodes in a longer-term operation, which must be harmful for the application of ER fluids in practice. Using a square field with $\pm E$ can alternately change the direction of the field and efficiently prevent such particle deposition, keeping a sustainable working environment.

4. Conclusion

The responses of the shear stress for PM-ER fluids on the electric field in alternate triangle and square electric field have been studied in a wide frequency range. Due to the relaxation effect of ER response, the shear stress cannot well follow a rapid changing electric field, which causes the average shear stress to decrease with the frequency increasing and become very low at high frequencies. The results indicate that in the applications of PM-ER fluids only an AC field with low frequency is suitable to be used, i.e., the shear stress cannot rapidly response the controlling electrical signal. However, the average shear stress of the PM-ER fluid still can keep at a high value in a square electric field with $\pm E$ at low frequencies. This character takes advantage to avoid possible deposition of the particles on the electrodes due to electrophoresis.

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