Electrorheological flow patterns analysis

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Abstract. A method of image analysis of flow patterns, which are developed in electrorheological fluids, is presented. Due to the process of preparation, electrorheological samples show a radial symmetry. Numerical transformations are necessary to remove sample deformation and obtain correct radial dependence of image intensity as the function characterizing the sample image. Parameters describing the radial symmetrical image are suggested. Then the influence of electrorheological parameters on properties of final sample is studied.

1. Introduction
Electrorheological (ER) fluids are systems whose rheological properties (viscosity, yield stress, shear modulus) can be controlled by external electric field. Polarized particles are oriented in the direction of electric field and create structures (chains), which increase the rigidity of the originally liquid system.

The arrangement of the particle chains in electric field has been proved via optical microscopy. A direct optical display of ER suspensions in rotational viscometer presented in papers [1–4] indicated that particles organize into lamellar or ring structures, which are optimal for minimum energy dissipation, and this structure depends on the flow field. The aim of this paper is to describe ring ER structures, using image analysis, with respect to conditions of their development.

2. Experimental
Rotational viscometer Bohlin Gemini (Malvern Instruments, UK) in parallel plates geometry (diameter 40 mm, gap 1 mm) was used for experiments. 20 and 40 wt. % suspensions of glass beads (40 µm) in liquid silicone rubber were sheared at various shear rates in the presence of electric field (1 kV mm⁻¹) and generated circular flow patterns were fixed via curing of silicone rubber matrix.

Later, samples were scanned on commercial scanner and greyscale images with typical size 1000×1000 pixels were obtained.

3. Methods of image analysis
As can be seen in figures 1, 3 and 4, circular structures developed during the flow of ER fluids upon application of electric field significantly depend on a value of shear rate used. At low shear rates higher number of thin rings is formed. With increasing shear rate, number of rings decreases while their width rises.
The goal of presented mathematical procedure is to describe ER ring patterns by some simple numbers defined by radial dependence of darkness of the image and to correlate them with conditions of their preparation.

3.1. Image preprocessing

Suppose that \( p(x,y) \) is brightness of pixel in \( x \)-column and \( y \)-row of the image. There are several problems to be solved prior analysis. Samples are relatively soft and easily deformable therefore images are slightly prolonged in some directions because of manipulation.

In the first step the centre of sample symmetry was detected as a point \( (x_c, y_c) \) minimizing the function \( S(x_c, y_c) \) (equation 1):

\[
S(x_c, y_c) = \sum_{x,y} \frac{(p(x + x_c, y + y_c) - p(x - x_c, y - y_c))^2}{\sqrt{x^2 + y^2}}
\]

where \( p(x,y) \) is brightness of \((x,y)\) pixel. Position of pixels \( p(x + x_c, y + y_c) \) and \( p(x - x_c, y - y_c) \) is symmetrical with respect to centre of symmetry \( (x_c, y_c) \). The numerator is the square of pixels in symmetrical positions. The expression in denominator is pixels distance \( r \) from centre \((x_c, y_c)\). The number of pixels in interval \( r; r + dr \) is proportional to radius \( r \). The denominator ensures the same weight of pixels in any distance from centre. Minimizing the function \( S(x_c, y_c) \) we obtain centre position for which the difference between points symmetrical with respect to it, are minimal.

If the centre is found, image is divided into 8 radial sectors and mean brightness as a function \( f_i(r) \) (index \( i \) denotes the sector) of the real centre distance \( r \) is computed for each sector. The functions \( f_i(r) \) and \( f_j(r) \) can be a little shifted (due inaccuracy of centre detection) and elongated due the sample deformation.

The generalized cross-correlation function (equation 2) [5]:

\[
(f_i * f_j)(h, x) = \int f_i(r) f_j(hr + x)dr
\]

is a tool for finding the best shift \( x \), and elongation \( h \) of function \( f_i \), maximizing the function \((f_i * f_j)\) and obtain the maximal similarity of \( f_i \) and \( f_j \). Then all functions for all sectors are averaged to obtain final \( f(r) \) function representing radial dependence of image brightness.

Figure 1. The original image (a), corresponding result of the image preprocessing (b) and appropriate \( f(r) \) function (c).

Thanks to such image preprocessing all artifacts as noise, sample inhomogeneities, sample deformation are removed (figure 1b) and then the function \( f(r) \) as radial intensity dependence is obtained (figure 1c).

3.2. Image quantities

After the image preprocessing some parameters for pattern characterization must be chosen. We see evident differences between samples prepared under different conditions, but we have to find some simple numbers to describe images differences. A contrast should characterize changes of intensities of image in radial direction (waviness or amplitude of \( f(r) \) function). A period describes mean width of rings (local extremes of \( f(r) \) function).
3.2.1. **Standard contrast** Standard contrast (amplitude of $f(r)$ function) is inspired by standard deviation in statistics: $\sigma = \sqrt{\frac{1}{N} \sum_{i} (x_i - \bar{x})^2}$. The function $c_s = \sqrt{\frac{1}{R} \int_{0}^{R} \left( f(r) - \frac{1}{R} \int_{0}^{R} f(r) dr \right)^2 dr}$ is generalisation of this well known statistical equation. It can be seen from definition that standard contrast is sensitive to size of local minima and maxima of function, but is not sensitive to behaviour of 1st derivation of function.

3.2.2. **Linear contrast** The linear contrast is inspired by linear roughness often used in engineer mechanics. The linear contrast of function $f(r)$ is defined as a length of function curve divided by a length of curve projection to horizontal line (equation 3):

$$c_L = \frac{1}{R} \int_{0}^{R} \sqrt{1 + f^{'2}(r)} dr$$

(3)

Figure 2. Model $f(r)$ functions and their contrast values.

The difference between standard contrast $c_S$ and linear contrast $c_L$ can be explained in the figure 2. Standard contrast is low for functions 2a and 2c (low amplitude). Linear contrast is low for functions 2a and 2b (slow intensity change with growing $r$). For 2b and 2d $c_S$ is high; $c_L$ is high for 2c and 2d.

3.2.3. **Period** Period $P$ is the mean distance between neighbouring $f(r)$ maxima, i.e. mean gap width of neighbouring bright pattern circles. It can be replied that $f(r)$ function is not periodic, but period is quantity describing mean density of rings.

4. **Results**

4.1. **Reproducibility**

The reproducibility of samples was tested on four samples produced at the same conditions (figure 3). It is evident that resulting images are very similar and suggested parameters have small variability.

Figure 3. Four samples produced by the same conditions (concentration 40 %; shear rate $\gamma=10$ s$^{-1}$; time=300 s; $E=1$ kV mm$^{-1}$) and their calculated parameters (period $P$ is measured in mm).
Figure 4 shows influence of shear rate and processing time on parameters of samples. It seems that both pattern contrasts and period increase with shear rate and processing time. The area of central unstructured part of samples is decreasing with growing time and shear rate. Probably a total plate displacement is important for structure progression. At time 1200 s and two higher shear rates a structure regression is observable (especially $c_S$). It seems that there is some optimal time which ensures pronounced structure progression.

5. Conclusion
The quantitative parameters for description of flow patterns, which are developed in electrorheological fluids, were suggested and verified. Growing processing time and shear rate leads to more perspicuous patterns, but the regression at higher shear rates should be properly examined.

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7. References
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