Birefringence of α-iron oxide (III) colloids using ultrasound

Yuma Kuroda[1†], Akira Emoto[2], and Daisuke Koyama[1*]
([1]Doshisha Univ.; [2]Tokushima Univ.)

1. Introduction

In 1936, Burger and Söllner first discussed particle manipulation in suspension using ultrasound[1)], and Lucas first observed birefringence in random-oriented colloids using traveling ultrasound in 1938[2)]. The theorical models for these phenomena have been discussed; birefringence of the colloid Δn is proportional to the square root of ultrasound intensity, the spatial gradient of particle velocity, and volume fraction[3-5)]. Ultrasound vibration can induce changes in the spatial distribution of birefringence of nematic liquid crystal[6)], and this technique can be applied to optical devices such as variable focus optical lenses[7,8)]. In this report, a method to generate spatial gradients of birefringence of colloids using ultrasound vibration is discussed.

2. Configuration and methods

Ultrasound colloid cells were fabricated (**Fig. 1**)[6)]. More than the saturated amount of α-iron oxide (III) powder (FE010PB, Kojundo Chemical Laboratory Co. Ltd) was added to 10% hydrochloric acid (085-07535, FUJIFILM Wako Pure Chemical Corporation). The colloid fabricated in the solution was filtered through a filter paper with a mesh size of 6 μm. A colloid layer with a thickness of 500 or 50 μm was fabricated via spacers between two rectangular glass substrates (width: 5 mm; length: 120 and 50 mm; thickness: 0.5 mm; Eagle XG), and the surrounding part was sealed with epoxy. Two rectangular piezoelectric lead zirconate titanate (PZT, C-213; thickness: 1 mm; width: 5 mm; length: 30 mm; Fuji Ceramics Corporation) transducers were attached to both sides of the glass substrate.

Alternating currents with the same amplitude and phase were input to the transducers so that the resonant flexural standing-wave mode can be generated in the length direction of the glass plate. The vibrational velocity of the cell was measured using a laser Doppler vibrometer (LDV, VIO130, Polytec). The transmitted light through the cell was evaluated using a two-dimensional birefringence profiler (**Fig. 2**)[9)] that converts birefringence in a sample into light intensity of the first diffraction light through a specific diffraction grating and measures the two-dimensional phase difference of the transmitted light using a digital camera[10)].

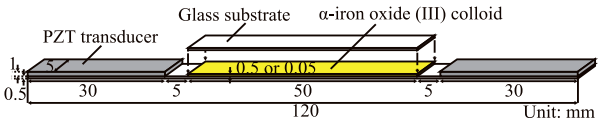

Fig. 1 Ultrasound colloid cell.

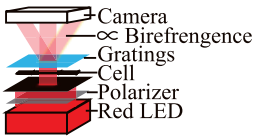

Fig. 2 Schematic of a birefringence profile.

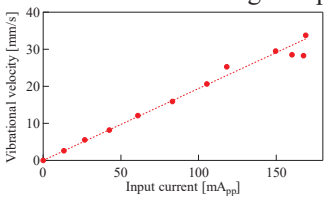

Fig. 3 Relationship between input current and vibrational velocity at 56 kHz.

3. Results and discussion

The ultrasound colloid cells had several resonant frequencies over 20 kHz, and the resonant flexural vibration in the length direction was generated at 56 kHz where the birefringence of the colloid was changed. The vibrational velocity of the cell with a colloid layer thickness of 50 μm was measured with changing the input current (**Fig. 3**). The single has optical anisotropy, but the birefringence does not appear in the colloid layer because the optical anisotropies are totally canceled each other in the initial random condition. Acoustic radiation force originated from differences in acoustic energy density between the glass substrates and the colloid layer is generated by the flexural vibration, resulting in orientations of the particles and changes in the phase difference of the transmitted light (birefringence of the colloid) spatially. The distribution of the phase difference of the transmitted light was measured (**Fig. 4(a)**). **Fig. 4(b)** shows the distributions of the phase differences of the transmitted light and the vibrational amplitude in the length direction in the case with several input voltages. The random noise signal with a low amplitude was observed in the phase difference distribution of the transmitted light in the absence of an input voltage, meaning the colloid particles were oriented randomly. In the cases with ultrasound excitation, the phase difference was increased significantly, and the increment at the center part of the cell was greater than those at both ends. The wavelength of the resonant flexural standing wave in the length direction was approximately 10 mm,

indicating the spatial cycles of the birefringence change were much greater than the wavelength of ultrasound vibration. These results implies that the acoustic radiation forces generated by the flexural vibration would act the colloid particle, resulting in the collective orientation of the colloid particles. Yasuda *et al.* reported that the relaxation time of 1.4-mm-thick α-iron oxide (III) cell by ultrasound traveling waves at 5 to 225 MHz followed the Debye-Einstein equation, and they concluded there would be no interparticle interaction in the orientational motions[5]. Iwamoto and Kumagai also reported that the dielectric relaxation time of gelatin follows the Debye-Einstein equation for diluted solutions, but not for concentrated solutions[11]. Considering the experimental condition in this work where the saturated colloid solution was used, the interparticle interaction of colloids and its viscosity should not be ignored.

Change in the birefringence was increased with the input current to the cell. The relationship between the input current and the phase difference of the transmitted light is shown in **Fig. 4(c)**. Plots and error bars indicate the median value and the interquartile range at the center part of the cell (26 mm, dotted line in Fig. 4(a)). The fitting lines were determined by the weighted least-squares method, and inverses of the interquartile range was used as the weights. When the input current was smaller than 70 mA_{pp}, the distributions of birefringence were changed randomly because of low signal-to-noise ratios. In the cases over 70 mA_{pp}, the phase difference was proportional to the input current, meaning the birefringence was proportional to the square root of the ultrasound intensity. This trend can be observed in the cases with ultrasound traveling waves[4]. Although the phase difference was increased with the thickness of the colloid cell, the 50-μm-thick colloid cell showed a larger ratio of the birefringence to the colloid thickness since the acoustic energy volume density would be large.

4. Conclusion

In this report, the birefringence of α-iron (III) oxide colloids was successfully changed by applying ultrasonic flexural standing waves. The spatial gradient was independent of the vibrational distribution of the resonant standing wave and showed its maximum value at the center of the cell due to the interparticle interaction. The change in birefringence induced by the resonant standing waves was proportional to the square root of the acoustic intensity.

Acknowledgment

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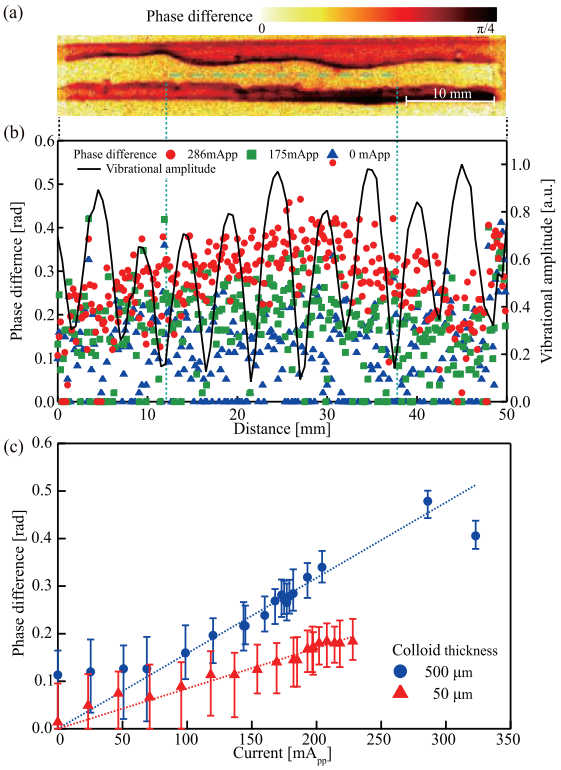

Fig.4 (a) Spatial distribution of the birefringence of the 500-μm-thick colloid cell at 175 mA_{pp}. (b) Distributions of birefringence and vibrational amplitude and (c) relationships between birefringence and input current at 56 kHz.

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