A novel Planetary Motion of Ferrofluid Drops in a Rotating Magnetic Field

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ABSTRACT

We experimentally investigate the motion of a ferrodrop array in a rotating magnetic field. The ferrodrops undergo interesting dual rotations, such as the local self-spins of individual drops and the global revolution of the drop array. While the drops spin nearly synchronized with the overall external field, the revolution always lags behind the field and appears a forth and back movement. Significance of the net revolutionary movement depends on the uniformity of the overall field distribution. In general, a more uniform rotating field leads to a more prominent global revolution of the array. Phenomenon of such dual rotations can be applied to mix two fluids more effectively than a self-spin drop.

Keywords: ferrofluid ; planetary motion ; rotational field

1 INTRODUCTION AND EXPERIMENTAL SETUPS

The dynamics of slender magnetic structures in a dynamical field, such as a chain consisted of magnetic beads in a rotating or an oscillating field, have been intensively studied in recent years [1-5]. This kind of magnetic devices can be applied as artificial swimmers [3,5] or active fluid mixers [6,7]. Inspired by these researches, a close resemblance is forming such a slender device by arraying ferrofluid drops, instead of chaining superparamagnetic beads. Dynamics of a single ferrofluid drop had been subjects of thorough studies, e.g. in a static magnetic field to determine the surface tension [8] and understandings of morphological evolution in a rotating field [9]. Nevertheless, motion of multiple drops aligned as an array, which is crucial for their manipulations in practical applications, has not yet drawn much attention. In addition, even the magnetic interactions between the magnetized drops mimic to the magnetic particles, the deformable surface would lead to a new phenomenon. This study intends to realize the motion of such a deformable drop array subjected to a rotating field. An interesting phenomenon of dual rotation, including the local self-spin and the global revolution, is reported. Sample experiments are also presented to demonstrate the capability as an effective active fluid mixer.

The experimental apparatus includes two pairs of coils powered by AC power sources and placed perpendicularly, designated as x- and y-axis. Two identical sinusoidal field components along the x- and y-axis are generated by the coils associated with a frequency of f=1 Hz. The overall external field ($\boldsymbol{H}$) composed by the two dynamical components is given by $\boldsymbol{H}=H_m\sin(2\pi ft+\triangle\theta_H)\boldsymbol{i}+H_m\sin(2\pi ft)\boldsymbol{j}$, where $\triangle\theta_H$ is the phase difference between $\boldsymbol{H_x}$ and $\boldsymbol{H_y}$. H_m is the reference field strength. Shown in Fig. 1 are the temporal evolutions of all the field components within one period of rotation, and the overall field strength distribution in a polar system as well. Three representative configurations of phase differences, e.g. $\triangle\theta_H$= 50^o, 70^o and 90^o, are presented. Under such a setup, an ideal rotating field with a constant angular speed and uniform field strength can be obtained if the phase difference is taken as $\triangle\theta_H$=90^o. Otherwise a wavering overall field is generated associated with variant angular speed, even the field still rotates periodically. As a result, the field distributions tend to more elliptical in the polar expressions if the phase differences deviate more significantly from $\triangle\theta_H$=90^o. In the study, light mineral oil ferrofluid (EMG905 produced by Ferrotch) drops surrounded by glycerin-water mixture are experimented. The viscosity, density and strength of saturated magnetization are μ_d=3 cP, ρ=1.2x10^3 kg/m^3 and Ms=440 G, respectively. The density of the glycerin-water mixture is nearly identical to the ferrofluids with a viscosity μ_m=120.6 cP. The motion of the drops is recorded by an optical microscope connected to a digital camera, which is incorporated with an image software to display snapshot images for further analysis.

2 RESULTS AND DISCUSSION

Motions of a single ferrofluid drop in a rotating field with various phase differences, such as $\triangle\theta_H$=50^o and 90^o, are first presented as shown in Fig. 2. It is known that an initially circular ferrofluid drop would be stretched to the shapes of ellipsoid along the orientation of the external field first, and an equilibrium state would be reached by the balance between the magnetic energy and the surface energy. In the meantime, the stretched ellipsoid is driven to rotate [9], referred to as the self-spin of drop therein. It is noticed that the drop spins almost synchronized with the external field in the present condition. Another interesting but not unexpected observation is that, while the elliptical shape of the self-spinning drop remains nearly unchanged for the case of an ideal rotating field, e.g. $\triangle\theta_H$= 90^o, the prominence of elongation varies during the self-spinning process in the field configuration of $\triangle\theta_H$= 50^o. As demonstrated in Fig. 1, the overall field strength is non-uniform under the present condition, so the drop is stretched more significantly when the simultaneous field strength is stronger. The orientation where the drop appears more significant elongation consists with the field distribution shown in Fig. 1(b). This fact implies a possible local control of the spinning drop if desired.

A question arises if multiple drops are placed in an array and subjected to the same field condition. Under such a condition, the interactions between magnetized drops would expect to play an important role. Shown in Fig. 3 are the snapshots of a three-drop array under field configurations of $\triangle\theta_H$=50^o, 70 ^{o} and 90^o. Similar to the case of a single drop, all the drops undergo local motions of self-spins. Nevertheless, an interesting global phenomenon of array revolution can also be identified. Contrary to the local self-spins which appear almost synchronized with the rotating field, this global revolutionary motion of the array does not follow the orientation of external field consistently. The drop array in a uniform rotating field of $\triangle\theta_H$=90^o undergoes an apparent overall revolution with the external field, i.e. counter-clockwise, but lagging behind greatly. On the other hand, the drop array in a strongly non-uniform rotating field of $\triangle\theta_H$=50^o merely shows a local oscillation. For the condition in a milder non-uniform rotating field of $\triangle\theta_H$=70^o, the array appears forth and back with a net counter-clockwise revolutionary movement within the period. Because of the inconsistent global revolution, the drop array usually does not align toward the same orientation with the overall field, so that full elongations of drops are allowed toward the simultaneous orientation of the overall field, e.g. examples shown the bottom row of Fig. 3. Nevertheless, when the alignment of the array is collateral to the simultaneous field, e.g. t=0.47s and 0.93s shown in the top row of Fig. 3, only the outward sides of the most outer drops can be stretched freely to form elliptical fronts. The shapes appear flatter at the sides adjacent to the neighbor drops. It is also interesting to notice that no drop coalescences occur between the adjacent drops in the present experimental condition. It is noticed that the drops can be in contact for sufficient strong field strength. Nevertheless, in the most commonly observed cases under the present experimental fluids, the drops retain separated if the field is turned off. An ongoing effort is devoted to explore the possibility of drop coalescences under different experimental conditions.

According to the experimental observations described in the above paragraph, a ferrodrop array driven by a rotating field undergoes an interesting motion of dual rotation, such as the local self-spin of individual drops and the global revolution of the array. Understandings of the local self-spins are straightforward, in which the orientation of elongation tends to follow along the orientations of the rotating field [9]. On the other hand, the global revolution of the drop array is attributed by the interactions between the magnetized drops, whose mechanism can be analogized to the magnetic bead chain subjected to rotational or oscillating fields [1-5]. By this analogy, the ferrofluid drops and array resemble the magnetic beads and the chain, respectively. Based on the assumption of point dipoles, the torque (T) generated by the external field to the magnetized chain or array can be approximated as T ~ sin(2$\triangle\theta_L$), where $\triangle\theta_L$ stands for the simultaneous phase difference between the external field and the alignment of drop array. This torque is driving source to the global revolution. To further understand this driving force, the trajectories of both the overall fields and drop arrays within one period of rotation for three field configurations are demonstrated in Fig. 4. For a uniform rotating field of $\triangle\theta_H$=90^o, the angular speed of the field is constant, so that the field trajectory is a straight line as shown in the figure. On the contrary, for the configurations of non-uniform fields, their trajectories appear wavering with variant angular speeds within rotation. At an earlier time stage, the fields move well ahead of the arrays for all three conditions and generate effective torques toward the orientations of the rotating fields, i.e. counter-clockwise, so that the arrays are driven to undergo global revolutions. Nevertheless, due to the significant hydrodynamic drags to resist the revolutionary motion, the phase lags ($\triangle\theta_L$) continue to grow. At a certain extent, the phase lags would exceed a critical value of $\triangle\theta_L$ > 90^o, and leads to a sign change of torque, i.e. T ~ sin(2$\triangle\theta_L$). Similar phenomenon had also been reported in a superparamegnatic chain, and was referred to as trajectory shift [5]. Then, the revolutionary movement of the drop array would be reversed. This reversed revolution would proceed till the direction of torque is changed again at $\triangle\theta_L$ > 180^o. Similar scenarios would proceed continuously afterward at the times when the phase lag exceeds the multiples of 90^o. The continuous alternation of torques explains the forth and back motion of the global revolutions. More detailed dynamics regarding the trajectory shift is referred to Ref.[5]. In addition, it is realized that the simultaneous angular speed of the external field at an early stage is the greatest for the most non-uniform rotating field of $\triangle\theta_H$=50^o, as shown in Fig. 4, so that a largest phase lag is resulted at the early time interval. As a result, the first reversed revolution occurs the earliest for $\triangle\theta_H$=50^o, as the vertical line marked by A1 shown in Fig. 4. By the same token, the first reversed revolutions for $\triangle\theta_H$=70 ^{o} and 90^o, marked by B1 and C1 respectively, will happen at later times subsequently. Fig. 4 shows that the trajectory of array has been shifted 4 times, e.g. A1~A4, for $\triangle\theta_H$=50^o, while there are only 3 shifts for $\triangle\theta_H$=70 ^{o} and 90^o, e.g. B1~B3 and C1~C3, respectively. The later and fewer occurrences of the reversed revolutions for more uniform rotating field conditions are the reasons of greater net revolutionary movements.

A potential application of this interesting dual rotation of a drop array is the enhancement of fluid mixings. Two sample experiments are shown in Fig. 5. Even the fluids can be actively mixed by the vortex generated by an elongated drop with self-spin as shown in the top row, the strengths of disturbances are further strengthened by the global revolution if a two-drop array is applied (bottom row). It should be noticed that the main issue shown in Fig. 5 is to demonstrate the mixing effectiveness resulted by the additional global revolution. The concern would be if the mixings of a two-drop array twice greater than a single drop in a more effective way? The results confirm that fluid mixings, represented by the increments of dyed areas (△A), are grater than twice by a single drop at early times, which indicates a more effective mixing.

3 CONCLUDING REMARKS

Driven by a rotating field, an interesting phenomenon of dual rotations is identified in arrayed ferrofluid drops, including a local self-spin of individual drops and the global revolution of the array. Because of the simultaneous realignments of the induced poles in the magnetized ferrofluids, the ferrodrops are elongated and spin nearly synchronized to the field. On the other hand, the global revolution of the drop array is resulted by the interactions between the magnetized drops, and might undergo a wave-like forth and back movement. The wavering behaviors of array revolutions are realized by the alternative magnetic torques acting to the array, which change sign when the phase lag between the orientations of the external field and the alignment of the array reaches multiples of $\pi/2$. Prominence of the net revolutionary movement is affected by the uniformity of the overall field distribution. In general, a more uniform rotating field leads to a more prominent global array revolution. Such dual rotations can be applied to enhance mixings of two fluids more effectively than a self-spin drop.

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REFERENCES

[1] S. Biswal and A. Gast, Phys. Rev. E 69, 041406 (2004).
[2] A. Cebers and I. Javaitis, Phys. Rev. E 69, 021404 (2004).
[3] Y.-H. Li, S.-T. Sheu, J.-M. Pai and C.-Y. Chen, J. Appl. Phys. 111, 07A924 (2012).
[4] Y.-H. Li, C.-Y. Chen, S.-T. Sheu and J.-M. Pai, Microfluid Nanofluid 13, 579 (2012).
[5] Y.-H. Li, H.-C. Lin and C.-Y. Chen, Microfluid Nanofluid, 14, 831 (2013).
[6] T. G. Kang, M. Hulsen, P. Anderson, J. den Toonder and H. Meijer, Phys. Rev. E 76, 066303 (2007).
[7] T. Roy T, A. Sinha, S. Chakraborty, R. Ganguly and I. Puri, Phys. Fluids 21, 027101 (2009).
[8] S. Afkhami, A. J. Tyler, Y. Renardy, M. R Renardy, T. G. St. Pierre, R. C. Woodward, and J. S. Riffle, J. Fluid Mech. 663, 358 (2010).
[9] A. Lebedev, A. Engel, K. Morozov and H. Bauke, *New J. Phys.* 5, 57 (2003).

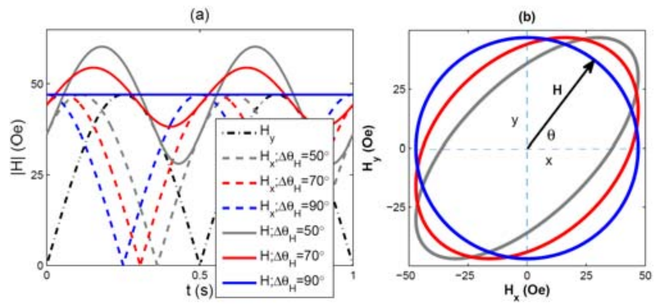

Fig.1: (a) Temporal evolutions of the magnetic fields within one period of rotation in various configurations of phase difference (denoted as $\triangle\theta_H$) between field components in x- (H_x) and y- (H_y) directions. (b) Distributions of the overall field (H) in a polar system. Strengths of the overall field at any angles (θ) are represented by the correspondent radial distances. A uniform rotating field can be obtained in a configuration of $\triangle\theta_H=90^o$. If the phase difference deviates more significantly from $\triangle\theta_H=90^o$, the temporal evolutions appear more wavering, and the field distributions tend to more elliptical.

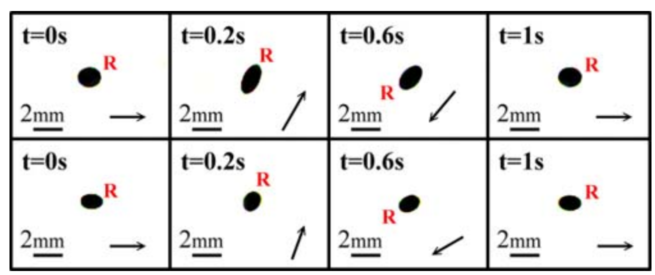

Fig. 2: Motion of a drop subjected to an overall field strength of H_m = 47 Oe and (top) $\triangle\theta_H=50^o$; (bottom) $\triangle\theta_H=90^o$. The directions and the lengths of arrows represent the simultaneous orientations and magnitudes of the overall field, respectively. The rotating field first stretches the initially circular drop to an ellipsoid, and then drive the drop to self-spin nearly synchronized with the external field. Because of temporal variation of the field strength for $\triangle\theta_H=50^o$ (top row), the elongations of drop are more significant at t=0.2s and 0.6s.

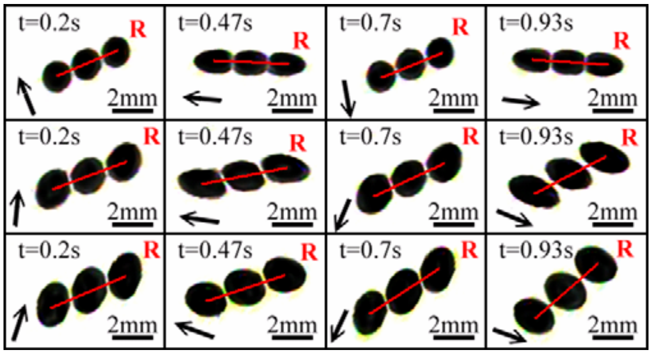

Fig. 3: Motion of a three-drop array at different times subjected to an overall field strength of $H_m = 47$ Oe and (top row) $\triangle\theta_H=50^o$; (middle row) $\triangle\theta_H=70^o$; (bottom row) $\triangle\theta_H=90^o$. The drop on the right and the axis of array revolution are marked by letter "R" and red lines, respectively, to demonstrate the global revolution of the array. Self-spins of individual drops nearly synchronized with the external field can be easily identified. In the meantime, the drop array in a uniform rotating field ($\triangle\theta_H=90^o$) undergoes an apparently counter-clockwise revolution, so that the while the array in the top row ($\triangle\theta_H=50^o$) merely shows a local oscillation. For the condition of $\triangle\theta_H=70^o$ (middle row), the array appears forth and back with a net revolutionary movement.

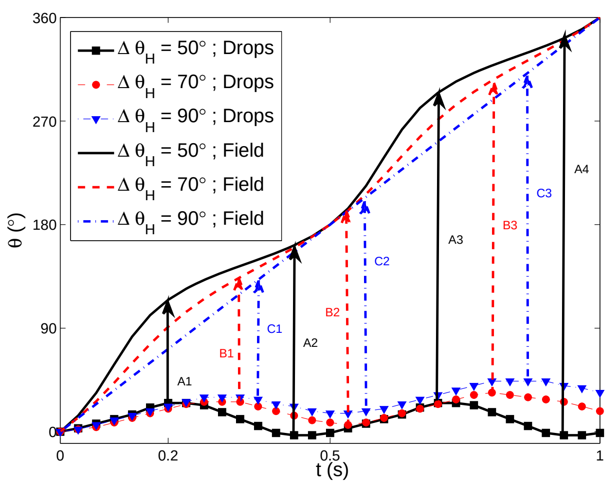

Fig. 4: Corresponding phase trajectories of the external fields and the drop arrays shown in Fig. 3. The vertical lines, marked by letters "A" , "B" and "C" to represent the configurations of $\triangle\theta_H=50^o$, 70^o and 90^o respectively, indicate the timings when the phase lags of the arrays to their corresponding fields reach the multiples of 90^o. All the trajectories of arrays show clearly forth and back movements. Nevertheless, a uniform rotating field of $\triangle\theta_H=90^o$ leads to a most effective advance of the revolutionary movement, while the phase trajectory for $\triangle\theta_H=50^o$ appears a local oscillation.

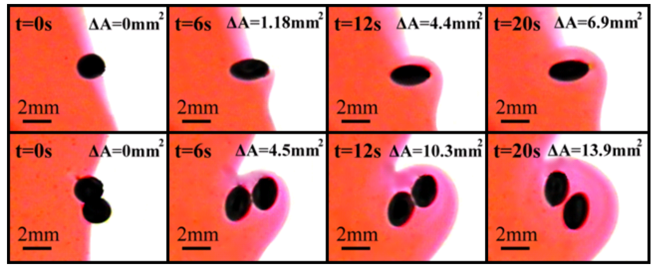

Fig. 5: Mixing effectiveness, represented by the increments of dyed areas ($\triangle A$), can be improved significantly by taking advantages of the dual rotations. Shown are drops in a field configuration of $\triangle\theta_H= 90^o$, so that the two-drop array undergoes both self spin and net revolutionary movement.