A “Map” of the Variations in Electrorotational Torque in Planar Electrodes

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Abstract

It is a well-established fact that the torque exerted on polarisable particles in rotating electric fields varies across the volume between the field-generating electrodes. In this paper we quantify that variation by measuring the rotation rates of elliptical beads in 203 positions about an electrorotation electrode array. It is demonstrated that the torque varies in excess of 50% according to the position within the array. By processing the rotation data to determine the underlying trends, we find that the variation closely matches the predicted form of torque variation predicted by numerical models, and verifies the predictions of a previously proposed model of the action of variations the electric field on the induced rotation of particles.

1. Introduction

The subject heading of "AC Electrokinetics" encompasses many phenomena, chief among them being dielectrophoresis and electrorotation. The former is the translational motion across a field gradient (eg. Pohl 1978); the latter is the rotational motion observed in rotating electric fields (eg. Arnold and Zimmermann 1988). Both motions are induced by interactions between field and induced dipole; since this relationship is dependent on the frequency of the applied field, studying particles exhibiting either behaviour allows particles to be "fingerprinted" according to its dielectric properties (Huang *et al* 1992).

In this work we are principally involved with the study of electrorotation. This technique has often been applied to the study of individual cells or other bioparticles within a population. This is due to the nature of the technique in that the particles remain largely stationary during the experiment (except under such conditions in which dielectrophoresis is also present). For example, this has allowed researchers to study the infection cycle of Herpes Simplex virions in cells (Archer *et al* 1997) or to identify the presence of bacteria adhered to the surface of rotating beads (Burt *et al* 1995).

One important drawback in electrorotation measurements is that the torque exerted on the particle is dependent of the magnitude and phase of the local electric field. These factors vary sufficiently for particles in one section of an electrode array to rotate significantly faster than those in another. This serves to make the rotation rates of particles in different areas incomparable. To avoid such problems, researchers restrict their measurements to small regions of the electrode array. For example, within the type of quadrature electrode array described here, Arnold and Zimmermann (1982) studied only those particles "within the central volume", Zhou *et al* (1994), "within the central region between the electrode tips", and Chan

et al (1997) restricted studies to those particles within a circle of radius defined by 1/3 of the distance from chamber centre to electrode tip. New systems are now being presented which "fix" particles in place during rotation measurement using laser tweezers (de Gasperis *et al* 1998)

Various studies have been performed using numerical simulation and field-mapping using large-scale electrodes (Gimsa *et al* 1987, Hölzel 1993, Hughes *et al* 1994) to determine the induced torque as a function of particle position within the chamber. The previous two studies were based on the principle that torque varies as a function of the square of the electric field; Hughes *et al* (1994) introduced the concept that torque is also related to phase differences across the rotation area. However, this model was never demonstrated to be correct in practical experimentation.

In this paper we attempt to determine the variation of electrorotational torque across the centre of a set of "polynomial" electrodes (Huang and Pethig 1991) commonly used in practical rotation experiments. The only previous attempt to form such a "rotation map" was performed by Fuhr *et al* (1987) by studying the variation of rotation speed of oat protoplasts across an electrode chamber formed by inserting four pins into solution. This study examined 17 points around the centre of the electrode chamber but recorded only a $\pm 10\%$ deviation in rotation rate. However, this was almost certainly due to the rounded, "3-dimensional" nature of the electrodes. Here we examine the rotation rate of uniform elliptical latex beads occupying 203 positions across a polynomial electrode array. This data, coupled with data processing to determine the underlying trends, exhibits striking similarities to the model predicted by Hughes *et al* (1994), implying that differences in the phase relationships play a significant role in determining the distribution of torque about the electrode array.

2. Theory

The general equation for time-averaged torque Γ experienced by a spherical polarisable particle of radius r suspended in a rotating electric field E is given in equation (1):

$$\Gamma = -4\pi\epsilon_m r^3 \text{Im}[K(\omega)]E^2 \quad (1)$$

Where ϵ_m is the permittivity of the suspending medium and $\text{Im}[K(\omega)]$ represents the imaginary component of the Clausius-Mossotti factor, shown in equation (2). The minus sign indicates that the dipole moment lags the electric field

$$K(\omega) = \left(\frac{\epsilon_p^* - \epsilon_m^*}{\epsilon_p^* + 2\epsilon_m^*} \right) \quad (2)$$

where ϵ_m^* and ϵ_p^* are the complex permittivities of the suspending medium and the particle respectively, and a general complex permittivity ϵ^* is given by: $\epsilon^* = \epsilon - j\frac{\sigma}{\omega}$ where σ is the

conductivity, ϵ is the permittivity, $j = \sqrt{-1}$ and ω is the angular velocity of the electric field.

When viscous drag is accounted for, the rotation rate $R(\omega)$ of the particle is given by (Arnold and Zimmerman 1988):

$$R(\omega) = -\frac{\epsilon_m \text{Im}[K(\omega)]E^2}{2\eta} \quad (3)$$

were η is the viscosity of the medium. Although for these experiments we have used ellipsoidal beads for which this treatment is rather more complex (Kakutani *et al* 1993), the principles of electrorotation described above still hold (Burt *et al* 1996).

Gimsa *et al* (1988) and later Hölzel (1993) performed non-time-variant studies of the electric field in polynomial electrodes for electrorotation. These studies presented time-averaged magnitude of the electric field, measured using large-scale electrodes and voltmeters, and compared with static electrical simulations. However, simulation of the dynamic electric field performed by Hughes *et al* (1994) suggested that both the *magnitude* and *phase* of the rotating electric field varied across the electrode plane. The latter is significant as it implies that the induced torque is dependent not only on the electric field but in the manner in which it rotates, which is rarely uniform. These workers concluded that an effective electric field factor $\mathbf{E}_{\text{eff}}^2$ could be used which compensated for this effect.

$$\mathbf{E}_{\text{eff}}^2 = \mathbf{E}_x \mathbf{E}_y \sin(\varphi_x - \varphi_y) \quad (4)$$

According to Hughes *et al* (1994), these factors are spatially dependent. This implies that the torque exerted on particles rotating in the electrode chamber varies as a function of position; in that paper Hughes *et al* gave diagrams of a postulated “rotation map” indicating that the torque varied by as much as a factor 2 depending on location within the electrode array. By examining the rotation rate across the electrodes using identical particles, it is theoretically possible to determine the way in which the torque varies across the chamber, and test the theory outlined above.

3. Materials and Methods

3.1 Electrodes

The electrode arrays used were of a polynomial design (Huang and Pethig 1991), with 400 μ m between opposing electrode tips. These were fabricated on glass slides by conventional photolithographic processes, using 100nm Au deposited over a 10nm Ti – 10nm Pa layer. The completed electrode array was enclosed using fast setting nail varnish and sealed with a coverslip. Total enclosed volume was approximately 10 μ l.

2.2 Experimental Setup

Experiments were performed using elliptical latex beads (Bangs Laboratories, Illinois) resuspended in 280 mM mannitol solution to a final concentration of approximately 2×10^7 ml⁻¹. The electrode array was powered by a 4-phase Direct Digital Synthesiser (DDS) at 1MHz, providing a 12V_{p-p} signal. Bead rotation was observed using a Nikon inverted microscope and recorded using a Panasonic digital camera and JVC S-VHS video recorder. Analysis of bead rotation was performed by playing back the videotaped experiments on a large video monitor, such that 400mm appeared as 36cm on-screen. Positions were measured to the nearest 1mm. Rotation rates were measured using a stopwatch to time 5 revolutions per bead. By redistributing beads after 1 minute of rotation by using a pipette, beads were measured in a total of 203 positions across the whole array.

4. Results

Figure 2 shows an image of beads rotating in the electrode array. On application of the electric field negative DEP was observed to push beads away from the electrode edges. Although particles were observed to rotate in this region, the DEP motion was too rapid to allow measurement of the rotation rate at a single point. Particles which did rotate near the electrodes, and inter-electrode gaps did so in a “jerky” manner where the bead alternated between rapid semicircular rotation and pauses where no motion was observed. These effects were observed up to about $50\mu\text{m}$ for the electrode edges.

Within the more stable region towards the centre of the array, beads rotated smoothly and the rotation rate could be determined. Figure 3(a) shows the distribution of rotation rate across the electrode chamber. The data shown is processed using the Matlab Delaunay triangulation function to interpolate between the data points, such that any point on the chart takes the value of the *nearest* recorded point to it. A total of 203 points were recorded, at the positions indicated in figure 3(b). Only those beads which were more than $10\mu\text{m}$ from the nearest neighbouring bead were measured in order to avoid dipole-dipole interactions. Rotation of the beads nearest to the electrode tips (some $50\mu\text{m}$ away from the tips themselves) was found to be approximately 1.5x greater than the mean rotation at the centre of the electrodes. The lowest rotation rates were found at the inter-electrode gaps, where values were typically 0.8x that at the electrode centre.

5. Discussion

5.1 Data Analysis

As can be seen from the data presented in figure 3(a), the rotation rate exhibits trends in behaviour – for example, the rate at the electrode tips is generally higher than at the centre or the electrode corners. However, there are local variations caused by differences in bead properties, height of the bead above the electrode plane, and friction caused by contact between bead and glass. In order to more accurately determine the general form of the torque distribution, we have performed further data analysis on the experimental results. The analyses fall into two categories: symmetry and averaging.

Since the polynomial electrode array is symmetrical about 4 axes, the data points collected across the array can be “mirrored” up to 8 times to effectively increase the number of points taken across the array by a factor of 8. Figure 4 shows the result of this operation as performed using the Matlab (Mathworks inc.) software suite. As can be seen, this makes the general form of the torque distribution clearer. The general form shows that the rotation is fairly constant across the central region, and rises towards the chamber edge. This rise continues towards the electrode tips, to a peak value of 1.5x the central average; nearer the tip this rise may be greater, but due to DEP forces no data was recorded near enough to the electrode edges to confirm this. In the direction of the inter-electrode gaps, the rise is seen to reach a “saddle point” before falling away to a value lower than that at the centre. These trends be emphasised by performing local averaging of data, where a rolling average is performed across predefined subareas. Figures 5(a)-5(c) show the results of figure 4 averaged using 10 μ m, 20 μ m and 40 μ m subareas respectively. As smoothing is increased, the general pattern is seen more clearly. The smoothed model (figure 4(c)) was tested for errors by subtracting the original data (shown in Figure 3(a)) from the smoothed data; variations were found to be

randomly distributed across the array, and were of the order of ± 0.15 x the average central torque value or less.

5.1 Comparison with Theoretical Model

In previous work (Hughes *et al* 1994) a simulation model of electrorotation effects in polynomial electrodes was presented. The model used Moments methods (Birtles *et al* 1973), to determine the torque variation across the electrode array. Here we have extended this model for comparison with the data collected, in order to determine the validity of the model.

The model is described in detail elsewhere (Hughes *et al.* 1994, Hughes *et al* 1996), but is summarised here. The dynamic rotating electric field was simulated by dividing the rotation cycle into 36×10^6 “frames” and determining the *static* electric field distribution in these instances. Calculations were performed using FORTRAN 77 on a VAX computer, and the results were processed using MATLAB to determine the spatial variation of the magnitude (E_x , E_y , E_z) and phase (ϕ_x , ϕ_y , ϕ_z) of the rotating field. The results of these simulations are described in detail by Hughes *et al* (1994)

The electric field was analysed across a plane extending $800 \times 800 \mu\text{m}$, covering the centre of the electrode chamber and $200 \mu\text{m}$ of the electrodes. The simulation space was divided into 80×80 discrete points, spaced $10 \mu\text{m}$ apart on a regular grid. The original simulation was performed in a plane $3 \mu\text{m}$ above the electrodes. Although the beads used here were $3 \mu\text{m}$ in diameter along the minor axis, at the distances from the electrodes described here the differences are minor, particularly if the beads are levitated above the electrode plane.

Figure 5 (a) shows the predicted distribution of E_{eff}^2 across the simulated plane, and figure 5(b) shows a close-up of the electrode chamber itself (defined by a box with an electrode tip at the centre of each edge). Comparing the centre region with the experimental results, and in particular with figure 4(c), a high degree of correlation is evident. The regions of 10%, 20% and 50% increase in rotation rate correspond very well to those values predicted in Hughes *et al* (1994). Also the general features – the shape of the central region, the rise towards the tips and the “saddle points” where the torque begins to decrease towards the electrode corners – are present in similar positions in both cases.

The principal discrepancy is that in experiments the torque near the inter-electrode gaps falls below that at the centre, whereas the model predicts that it should be of about the same magnitude. However, the model does predict that torque should fall below the mean central value further into the inter-electrode gaps, some 50 μm further away from the centre. Similarly, in Hughes *et al* (1994) a model for a semi-circular electrode predicts a reduction of torque at the corner of the electrode geometry would fall below the mean value at the centre. This may imply that the onset of the reduction in rotation rate may be due to differences between the simulated and experimental electrode geometries. Another reason for this behaviour may be due to the magnitudes of the rotating vectors E_x and E_y . If the magnitudes of these vectors differ significantly a non-spherical bead will vary in rotation rate depending on its orientation. Non-spherical objects such as the beads used here will typically tend to orient their major axis along the electric field vector. Such alignments would tend to cause ‘jerky’ rotation as reported, and would slow down bead rotation rate. Finally, near the electrode array the electric field contains a significant z -direction component, which may cause the particle to either align with the field or to rotate in a plane at an angle to that of the electrodes. Either of these behaviours would inhibit rotation to a degree.

6. Conclusions

By measuring the rotation rate across the centre of an electrode array, it has been shown that the torque varies by in excess of 50% according to the position within the array. This variation closely matches the predicted form of torque variation predicted by numerical models, and verifies the predictions of a previously proposed model of the action of variations the electric field on the inducted rotation of particles.

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Figures

1. A photograph of the electrodes used in this study. Electrodes are fabricated of 100nm Au over 10nm Ti/10nm Pa seed layer on glass slides. Electrodes are powered by a custom-build Direct Digital Synthesiser, providing 4-phase signals. Scale bar: 200 μ m

2. A captured video image of elliptical beads rotating in an electric field. Note that the beads are repelled from the electrode edges by dielectrophoresis, rendering it impossible to make measurements in this region. Only those beads more than $10\mu\text{m}$ from adjacent beads were used for this experiment. Scale bar: $100\mu\text{m}$

3. Results of measurements of rotation rate across the electrode chamber, defined by the box enclosed by the electrode tips. (a) The measured rotation rate, relative to the value at the centre of the electrodes. Values between the data points are represented by "plateaux" of value equal to that of the *nearest* data point. (b) A plot of the location of the data points used in this study. A total of 203 measurements were made.

4. As the electrode array used in these experiments is symmetrical in 4 planes, it is in principle valid to "mirror" data points across each of these planes of symmetry, thereby effectively increasing the resolution eightfold. The figure above shows the distribution relative to the central value for a fully-mirrored data set

5. The above figures show the result of applying a rolling average of defined size across the data set described in figure 4. (a) $10\mu\text{m}$ (b) $20\mu\text{m}$ (c) $40\mu\text{m}$. As the size of the subarea is increased, the general trends in torque distribution emerge.

6. (a) A simulation of the torque factor relative to the central value across the plane $3\mu\text{m}$ above the electrode surfaces. The simulation covers an area $200\mu\text{m}$ larger than the electrodes in both directions; the curvature of the electrodes is visible. (b) A close-up image of the relative torque, showing only the regions at the centre of the electrode chamber, defined by the box enclosed by the electrode tips. Compare this distribution with the experimentally determined underlying torque distribution (figure 5(c))