Measurement of viscoelastic characteristics of particles by the dielectrophoresis method

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Viscoelastic characteristics of biological particles have been measured based on theoretical and experimental analysis of established deformation oscillations of these particles under the effect of the inhomogeneous alternating electromagnetic field. An electromechanical model of a particle has been developed along with the software for measuring viscoelastic characteristics of biological particles by the dielectrophoresis method based on the electromechanical model proposed. In measurements of viscoelastic characteristics, human erythrocytes were used. Measurements involving computer processing of video images of erythrocyte motion and oscillations yielded the generalized stiffness coefficient for the studied population of erythrocytes $k = (3.8 \pm 0.9) \cdot 10^{-5}$ N/m and the generalized viscosity coefficient $\eta_c = (0.9 \pm 0.2)$ Pa · s. The technique proposed can form the basis for identification of biological particles.

Introduction

It is well-known that the atmosphere contains a lot of aerosol particles of biological origin. So analysis of the biological component of the atmospheric aerosol is of interest. One of the features of biological particles is their high deformability as compared to the particles of inorganic origin, which indicates a significant difference in their viscoelastic characteristics. Measurement of viscoelastic characteristics is important for development of devices measuring the concentration of biological particles in the atmosphere.

The aim of this work was to develop an electromechanical model of a particle and to measure, based on this model, the viscoelastic characteristics of particles using human blood erythrocytes as an example.

A particle in an inhomogeneous electric field is under the effect of the dielectrophoretic force, which can be expressed through the dipole moment d induced by the fields or through the polarizability of the particle α_c as[1]:

$$\mathbf{F} = (\mathbf{d}, \nabla) \cdot \mathbf{E} = \alpha_c \, \varepsilon_0 (\mathbf{E}, \nabla) \cdot \mathbf{E}, \qquad (1)$$

where $\mathbf{E} = \mathbf{E}_0 \sin(\omega t)$ is the external field; ε_0 is the electric constant. The force acting on the particle in the harmonic high-frequency field can be obtained by averaging[1] over the period of field oscillations:

$$\langle \mathbf{F} \rangle = \frac{1}{2} \alpha_c \, \varepsilon_0 (\mathbf{E}_0, \nabla) \cdot \mathbf{E}_0. \qquad (2)$$

It should be also noted that the magnitude of the induced dipole moment and, consequently, the particle polarizability depend both on the electric properties of the medium and the properties of the biological particle, as well as on the frequency of the alternating electric field.

Under the conditions of the inhomogeneous electric field acting on the particle moving in a liquid, the mean speed of translational motion of the particle v_c is determined by the condition of equality between the average force $\langle \mathbf{F} \rangle$ and the friction force $\mathbf{F}_{fr}$, related to the speed of the ellipsoidal particle as[2]:

$$\mathbf{F}_{fr} = 6\pi\eta_w R v_c, \qquad (3)$$

where η_w is the dynamic viscosity of liquid; R is the equivalent radius of the particle for motion in the direction of the semiaxis a:

$$R = \frac{8}{3} \frac{1}{\chi_0 + \gamma_0 a^2}, \qquad (4)$$

where

$$\chi_0 = \int_0^\infty \frac{d\lambda}{D}; \qquad \gamma_0 = \int_0^\infty \frac{d\lambda}{(a^2 + \lambda) D};$$

$$D = \sqrt{(a^2 + \lambda)(b^2 + \lambda)(c^2 + \lambda)},$$

a, b, and c are ellipsoid semiaxes.

Electromechanical model of a particle

The electromechanical model of a biological particle used in this work is shown in Fig. 1. In the general case, the projection of the biological particle into the 2D space is an ellipse with the relation between the large and small semiaxes varying from one particle to another. Two springs set at the right angle model elastic elements of the particle skeleton and account for membrane tension.

Under the effect of the electric field and following redistribution of ions inside the particle,

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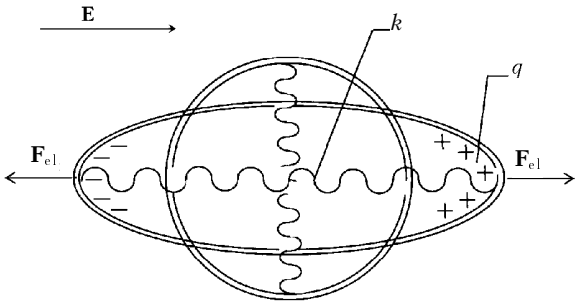

Fig. 1. Electromechanical model of a biological particle.

the induced dipole is formed. At the electric field strength $E \sim 10^5$ V/m, the particle, polarized in such a way, is under the effect of the electric force $\mathbf{F}_{el}$, which causes its deformation. In the model proposed, the particle membrane is assumed elastic and capable of transferring tension to the spring normal to the force direction. Since the particle volume has no time to change in the process of oscillations, the elastic elements normal to the field are related with the longitudinal ones, and, thus, we can consider one-dimensional oscillations with some generalized stiffness, including the stiffness of both the membrane and all elastic elements caused by the internal structure of a biological object. Therefore, speaking about the particle stiffness, we mean its *generalized* stiffness coefficient k, with which the particle opposes to the disturbing force.

Experimental technique and conditions

As a particle for direct measuring viscoelastic characteristics and, consequently, testing the proposed model of a particle, we used human blood erythrocytes. The following procedure was used to measure the viscoelastic characteristics of the particle. A measurement cell was set on a movable table of a microscope and fixed on it. The microscope was focused on an electrode edge near the measurement chamber.[3] A fresh suspension of particles was placed with a pipette under a cover glass in the measurement chamber. Once the suspension filled the space of the measurement chamber and came to the rest, it was subjected to the harmonic electric field with the mean strength $E = (1.6 \pm 0.1) \cdot 10^5$ V/m and the frequency $(1.00 \pm 0.05) \cdot 10^6$ Hz, lying in the region of positive dielectrophoresis, where the erythrocytes moved to the electrodes. Once the erythrocytes fell in the gap between the electrodes, the voltage modulation in the form of meander was turned on. As a result of interaction with the electric field, the erythrocytes are deformed, i.e., elongated along the force lines. The transformation of the erythrocytes from their placement under the cover glass to deposition on the electrodes was controlled and recorded with video facilities. The recorded video was input into the computer for further processing with a specially developed program, which determined the size, speed of translational motion, and amplitude of deformation of individual observed particles.

Mathematical model and algorithm for calculation of viscoelastic characteristics of particles

The deformation of the particles is described by the following differential equation:

$$m\frac{\mathrm{d}^2x}{\mathrm{d}t^2} + \mu\frac{\mathrm{d}x}{\mathrm{d}t} + kx = F_{el}H\left(\frac{T}{2} - t\right), \qquad (5)$$

where x is the displacement of the polar point of the particle; m is the effective mass taking part in the oscillations; μ is the generalized viscosity coefficient; k is the generalized stiffness coefficient; H is the Heaviside stepwise function. Equation (5) can be written in the following expanded form:

$$m\frac{\mathrm{d}^2x}{\mathrm{d}t^2} + 6\pi\eta_c R\frac{\mathrm{d}x}{\mathrm{d}t} + kx = \frac{\alpha_c\varepsilon_0 E_0^{\,2}}{4a}H\left(\frac{T}{2} - t\right), \qquad (6)$$

where η_c is the generalized dynamic viscosity of the cell; F_{el} can be written in the form

$$F_{el} = \langle qE \rangle, \qquad (7)$$

where q is the charge induced on a particle in the alternating electric field.

To find q the following algorithm was used. The polarizability α_c for every erythrocyte was calculated from the equality of the right-hand sides of Eqs. (1) and (3), using the established speed of the particle motion (the dielectrophoresis force is balanced by the liquid resistance force). Then the charge was determined as

$$q = \frac{d}{2a} = \frac{\alpha_c\varepsilon_0 E}{2a}, \qquad (8)$$

where d is the particle dipole moment induced in the alternating electric field, a is the large semiaxis of the ellipsoid particle. Thus, for the force after averaging we obtain:

$$F_{el} = \frac{\alpha_c\varepsilon_0 E_0^2}{4a}. \qquad (9)$$

For the resistance force experienced by the oscillating particle, we use the equation obtained for the translational motion on the assumption of the low oscillation frequency

$$\frac{l^2\omega\rho_w}{\eta_w} \approx 10^{-3} \ll 1, \qquad (10)$$

(here $l \approx 10^{-5}$ m is the characteristic size of the oscillating cell; $\omega \approx 10$ rad/s is the frequency of cell oscillations; $\rho_w \approx 10^3$ kg/m^3 is the liquid density) and the small Reynolds number

$$\mathrm{Re} = \frac{\omega l A \rho_w}{\eta_w} \approx 10^{-3} \ll 1, \qquad (11)$$

where $A \approx 10^{-5}$ m is the amplitude of cell oscillations, the liquid motion at every instant can be considered as stationary.[4]

The solution of the inhomogeneous differential equation (6) is well known[5] and at strong viscous forces

$$\frac{6\pi\eta_c R}{2m} \gg \sqrt{\frac{k}{m}} \qquad (12)$$

has the form

$$x = \frac{F_{el}}{k}\left(1 - e^{-\alpha t}\right); \quad nT \le t \le \left(n + \frac{1}{2}\right)T;$$
$$x = \frac{F_{el}}{k}\left(e^{\alpha T/2} - 1\right)e^{-\alpha t}; \quad \left(n + \frac{1}{2}\right)T < t \le (n+1)T, \qquad (13)$$

where

$$\alpha = \frac{k}{6\pi\eta_c R}, \quad n = 0, 1, 2, \ldots .$$

The program recognized all erythrocytes and determined their size and polarizability coefficients. Then the array of data on the amplitudes of particle oscillations at every instant was compiled. The obtained array of experimental data was numerically approximated by the theoretical curves $x(t)$ using the least square method (smooth solid curve in Fig. 2). The approximation yields α and P, where $P = F_{el}/k$. Knowing these parameters and the strength of the electric field F_{el}, with which the particle is stretches, we can calculate the generalized viscosity and stiffness coefficients of the particle.

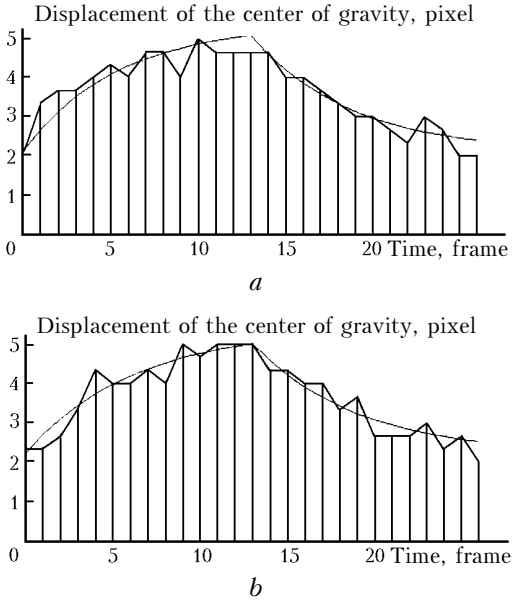

Fig. 2. Example of the program results for approximation of experimental data and calculation of viscous characteristics: $\alpha_c = 7.3 \cdot 10^{-15}$ m^3, $F_{el} = 10^{-10}$ N, $k = 3.1 \cdot 10^{-5}$ N/m, $\eta_c = 6.8 \cdot 10^{-1}$ Pa · s (*a*); $\alpha_c = 9.3 \cdot 10^{-15}$ m^3, $F_{el} = 1.5 \cdot 10^{-10}$ N, $k = 4.6 \cdot 10^{-5}$ N/m, $\eta_c = 1.3$ Pa · s (*b*).

Results

Observations of the deformation oscillations of erythrocytes have shown that their population includes both easily deformable and hard-to-deform particles. The viscoelastic characteristics calculated for the population studied are tabulated below.

Calculated viscoelastic characteristics

Erythrocyte #	$\alpha_c \cdot 10^{-15}$ m^3	$k \cdot 10^{-5}$ N/m	η_c, Pa · s
1	4.2	2	0.7
2	7.3	3.1	0.7
3	3.5	2.7	0.5
4	6.8	7.5	1.6
5	9.3	4.6	1.3
6	5.5	3.2	0.2
7	4.6	3.5	0.7
8	4.9	6.2	1.2
9	8.7	2.3	0.7
10	3.5	3.8	0.9
11	7.3	2.8	1.1
12	5.8	1.7	0.9
13	2.9	5.6	1.5
14	2.4	3.4	1.2
15	6.3	4.1	0.5
Mean	5.5	3.8	0.9
Standard error	1.2	0.9	0.2

For each erythrocyte we conducted three measurements (the experimental data were approximated over three periods of established oscillations, each including 26 points), since after that the standard error became comparable with the instrumental error and therefore the further increase of the number of measurements was unnecessary. Thus, the resulting measurement error is determined by the instrumental errors.

Analysis and discussion

Observations of the behavior of erythrocytes in the inhomogeneous alternating electric field, as well as the analysis of the results obtained have shown that erythrocytes deform in the pulsed inhomogeneous electric field, and the degree of deformation depends on their individual viscoelastic properties. It should be noted that the undoubted advantage of the dielectrophoresis method applied to measuring the viscoelastic characteristics is a conservation of vitality of biological particles.

The mean value of the generalized stiffness coefficient obtained by this method well agrees within the error magnitude with the published values of erythrocyte membrane tension[6] ($\sim 10^{-6}$ N/m), while no measurement data on the coefficient of generalized viscosity of erythrocytes are available in the literature.

The method proposed can serve as a basis for identification of particle vitality. It should be noted that as the membrane is broken, the particle polarization decreases.[7,8] The value of the induced dipole moment in this situation also decreases sharply, which causes a weak interaction of the particle with the inhomogeneous alternating electric

field. Particles with the defective membrane are not attracted to the electrode and deformed.

The described method can also be a basis for studying the interaction of some or other virus with a biological particle, since the virus penetrating into a particle also disturbs the integrity of its membrane and thus probably causes a sharp decrease in the amplitude of particle oscillations.

In addition, this method can be used in development of clinicodiagnostic express-methods for identification of diabetes, cholesterolosis, and some other diseases, since it allows measuring the mean stiffness and viscosity coefficients for the studied population of erythrocytes for 2–3 min.

The measurement of viscoelastic characteristics of particles can be also applied to identification of biological particles in the atmosphere using high-frequency electric fields.

It is well known that the strength of electric fields in the atmosphere can vary from 300 to 10^6 V/m depending on weather conditions, thus causing deformation of liquid particles. It is also known that the light scattering by particles in disperse media is directly related to the shape of scattering objects. Correspondingly, their deformation can significantly change optical characteristics of the medium.

Conclusion

In this work, we have measured the viscoelastic characteristics of biological particles based on theoretical and experimental analysis of their established deformation oscillations under the effect of the periodic inhomogeneous alternating electric field.

The following results have been obtained:

– the electromechanical model of a particle has been proposed;

– the specialized software has been developed for measuring the viscoelastic characteristics of biological particles by the dielectrophoresis method;

– the viscoelastic characteristics of biological particles have been measured for human blood erythrocytes taken as an example through processing of video records of particle motion and oscillation;

– the mean (for the erythrocyte population under study) value of the generalized stiffness coefficient has been obtained, and this value turned out to be in agreement with the values obtained by other authors based on other methods;

– the mean (for the erythrocyte population under study) value of the generalized viscosity coefficient has been obtained.

Acknowledgments

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