The best sensitive single-coordinate interference jet-drop measurement of electric field strength

E V Leun

Lavochkin Association, 24 str. Leningradskaya, Khimki, 141402, Russia
stankin1999@mail.ru

Abstract. The article discusses the features of the implementation of highly sensitive single-coordinate measurements of electric field strength (EFS) by using of jet-drop optical measuring systems (JDOMS). The use of moving monodisperse charged droplets of a jet-drop coherent flow, which acquire a displacement depending on the directions of movement, the level of the EFS and of the droplet charge, is discussed. The issues of implementation of stroboscopic interference measurements of droplet displacements under impulsed illumination of their surfaces, used as curved reflectors, are considered in JDOMS. It is shown that measuring the displacements of the reflected oh drop of the laser beam makes it possible to determine the displacements of the reflecting drop and the value of the EFS at the selected coordinate, respectively. The features of the use of liquids with pigments and additives in the form of nanopowders of highly reflective metals, liquid metals (or their alloys) with a low melting point are considered in the JDOMS.

1. Introduction

Measurement and control of electric field strength (EFS) $E$ and/or static charge $q$ are relevant for nuclear, rocket and space, electrical and radio engineering, instrumentation and other industries. And the tasks of preventing electrostatic breakdown and/or ensuring electromagnetic compatibility are especially important for many electrical devices at all stages of creation and operation. For this purpose, methods and means of measuring EFS $E$ are being actively developed on the basis of different principles of action [1-5]. To solve various applied problems, jet-drop technologies are also being improved, allowing to obtain unique properties for applications, in particular, in refrigerators-emitters of spacecraft [6,7], in electroplating technologies for inkjet printing [6,8], marking, dyeing and washing of fibers and threads [6,9], impulsed radiation sources in the ultraviolet range [10], increasing the efficiency of fuel combustion in aircraft engines [11], technologies for the formation of mono-dispersed spherical granules [12] and other tasks. In this regard, the natural aspiration is to search for original technical solutions for measuring systems of a new type - jet-drop optical measuring systems (JDOMS) [13-15] in relation to measurements of EFS, in particular, acousto-optical (AO) interference methods of information processing. The issues of creating such methods of measuring EFS are not reflected in the open press and this article is aimed at filling this shortcoming. The article discusses the features of the implementation of highly sensitive single-coordinate measurements of EFS.

2. Formulation of the problem

The main objective of this work is to study the developed method of measuring EFS and JDOMS based on jet-drop technologies and acousto-optical interference methods for measuring laser beam displacements. To solve this problem, the dependence of the deviation of moving charged droplets from the EFS is investigated,
the dependences of the deviation of the reflected optical flow from the displacement of moving charged droplets are determined, and the sensitivity threshold is estimated when measuring the EFS.

3. Theory

To measure the EFS along one coordinate on the basis of an electric jet generator and a impulsed interference meter of droplet displacements (in future - an interference meter), an interference JDOMS has been developed, the composition, principle of operation and features of which are discussed below.

3.1. Structure and principle of operation of JDOMS for measuring EFS.

The developed JDOMS for monitoring the EFS is shown in figure 1, which indicates a droplet generator 1, a jet consisting of a non-formed part of the jet 2 and a drip stream 3, a charger (a device for communicating a unipolar charge to drops) 4, the interference meter 5.

Under the action of constant pressure and additional perturbation created by the monoharmonic (with high spectral purity) signal $U_g(t)$, a liquid jet flows out of the droplet generator 1 through the nozzle in the forced capillary decay mode. This liquid jet consists of a non-formed part of the jet 2 and a stream of moving droplets 3 with a diameter of at least more than 1-1.5 mm with high monodispersity (small size spread) and coherence (small spread of intervals between drops).

In the process of separation from the jet, each drop is charged from the charger 4 to the $q_{drop}$ value. A charged moving drop, flying through the measuring section $l_{meas}$, deviates by a value corresponding to the action of the EFS.

In accordance with the results of calculations of displacements of a moving drop $\Delta l_{drop}$ carried out in [8,9] and by analogy with the electric field created by two plane-parallel deflecting plates with a length $l_o$ [9] forming a measuring section $l_o=l_{meas}$, provided that the influence of the charge field of this drop is neglected, we have $E=U_0/l_o$ and we can write:

$$\Delta l_{drop} = \frac{l_{meas}^2}{2 \cdot v_{drop}^2 \cdot m_{drop}} \cdot q_{drop} \cdot E,$$

where $l_{meas}$ is the length of the measuring section, $v_{drop}$, $q_{drop}$ and $m_{drop}$ are the speed, charge and mass of the drop.

Synchronously with the flight of the droplet, at certain points in the measurement cycle, the droplet is impulsed with a laser beam, forming a corresponding reflected stream. During a zero EFS $E_{meas}=0$, the position of the reflected flow is a reference. And when measuring a non-zero EFS $E_{meas}$≠0, this reflected flow acquires an angular and linear displacement of $\Delta l_{dis}$, according to the measurement results of which it is
possible to determine the displacement of the drop $\Delta l_{\text{drop}}$. This is how stroboscopic triangulation measurements of the displacement of the droplet are realized by an interference meter 5.

3.2. Structure and principle of operation of the interference meter.

To measure the deviations of droplet motion, a highly sensitive interference meter 5 is used, which is a laser impulse interferometer of Mach-Zender displacements with two arms, designed for high-precision measurements of transverse displacements of the laser flux in the task of controlling deviations from straightness [16]. Its scheme is shown in figure 2, which shows a impulsed laser 6, a beam splitter 7, a drop 8, an optical circuit 9, an AO modulator 10, microlenses 11 and 12 of the input 13 and 14 light guides of a Y-shaped fiber splitter 15, a photodetector 16, a running AO impulse 17.

The principle of operation is based on the impulse measurement of the phase shift of light waves arising from displacements of the center of AO interaction due to transverse displacements of the reflected laser beam $\Delta l_{\text{ref}}$ from the displacements of the droplet $\Delta l_{\text{drop}}$. It uses the diffraction of light in the Bragg mode on a short ultrasonic waves (USW), a "diffraction window" running through the AO modulator 10. The physical aspects of such modes of laser measuring systems (LMS) operation are considered in [16].

During the action of the light impulse, the streams pass through the following routes:
- in the reference arm: $A \rightarrow B \rightarrow$ photodetector 16,
- in the measuring arm: $A \rightarrow D$ (drop surface) $\rightarrow E \rightarrow F \rightarrow G \rightarrow$ photodetector 16.

Spatial alignment of the reference and measuring flows during the light impulse leads to their interference and the formation of an impulsion signal at the output of the photodetector 16.

Offset drops $\Delta l_{\text{drop}}$ alter the angle of reflection and the transverse displacements of the laser beam with the passage of the optical flow in the measuring shoulder along the following route: D (the surface of the drop) $\rightarrow E \rightarrow F \rightarrow G \rightarrow$ photodetector 16.

As shown in [16], the phase shift $\Delta \phi(\Delta l_b)$ caused by transverse displacements of the laser beam $\Delta l_b$ can be written using the expression:

$$\Delta \phi(\Delta l_b) = \frac{2\pi \Delta l_b}{\lambda} = k_b \frac{2\pi \Delta l_b}{\lambda},$$

(2)

where $k_b$ is the "angular" coefficient.

And then the expression for calculating the displacement of the optical flow $\Delta l_{\text{ref}}$ from the measured phase shift $\Delta \phi(\Delta l_b)$ can be written as:

$$\Delta l_{\text{ref}} = \frac{\Delta \phi(\Delta l_b)}{2\pi} \cdot k_b \lambda.$$

(3)

The limit resolution (threshold offset) $\Delta l_{\text{lim}}$ currently achieved in practice for similar LMS can be $\Delta l_{\text{lim}} = \lambda/135 \approx 0.005 \mu m = 5 \cdot 10^{-9} m$ at $\lambda = 0.63 \mu m$ [16].

3.3. Features of the use of liquids in the JDAMS EFS.

At large angles of incidence of light on the surface of the drop (>60°), the reflection from it approaches the mirror. An increase in the reflection coefficient is possible due to the use of special inks based on a solution with an opaque dye (with high radiation absorption) and/or a metallic pigment based on metal nanopowders (aluminum, bronze, copper, incl. with additives "similar gold") with particle sizes <50-100 nm with a high reflection coefficient.

Molten metals or their alloys can also be used as a liquid. Thus, melts of metals of the alkaline group or lithium (Li), potassium (K), sodium (Na) have a density less than that of water: 539, 862, 986 (kg/m³), and the surface tension of 0.400, 0.110, 0.205 (N/m) is greater than that of water. With such data, it is possible to increase the ratio $\dfrac{q_{\text{drop}}}{m_{\text{drop}}}$ and the sensitivity of the EFS measurements, respectively.

3.4. Determination of the angular displacement of the light reflected from the droplet.

Determination of the dependence of the angle between the incident and reflected light flows on the displacement of the center of the illumination spot relative to the radius of the drop during a perpendicular
displacement of the drop relative to the incident beam is possible using the optical scheme in figure 3. In this scheme, the angle of incidence of light $\alpha$ is equivalent to the angle of the OCA, and then from the aspect ratios of the right triangle OCA, we can get a formula for calculating the angle of reflection the laser beam is relative to the normal to the surface of the drop:

$$\frac{\Delta \alpha_{\text{ref}}}{\Delta \alpha_{\text{dis}}} = \frac{r_{\text{drop}} - \Delta l_{\text{dis}}}{r_{\text{drop}}} = \sin \alpha_{\text{ref}}' \tag{4}$$

From where it is possible to obtain an expression for $\alpha_{\text{gen}}$, taking into account that the angle between the incident and reflected streams is equal to the double angle of reflection relative to the normal to the surface of the drop $\alpha_{\text{gen}} = 2\alpha_{\text{ref}}$.

$$\alpha_{\text{gen}} = 2\alpha_{\text{ref}} = 2\arcsin \left( \frac{r_{\text{drop}} - \Delta l_{\text{dis}}}{r_{\text{drop}}} \right) = 2\arcsin \left( 1 - \frac{\Delta l_{\text{dis}}}{r_{\text{drop}}} \right), \tag{5}$$

where $\Delta l_{\text{dis}}$ is the displacement of the center of the illumination spot from the boundary of the drop, $r_{\text{drop}}$ is the radius of the drop.

3.5. Features of the use of the optical system.

The structure, characteristics, features of the optical system 9 and the parameters of light diffraction in the AO modulator 10 strongly influence the process of converting measurement information to an interference meter 5 (figure 2) and, accordingly, on the methods for calculating the displacement of the optical flow reflected from the drop. Their two possible variants can be based, first of all, on taking into account mainly angular or linear displacements of the reflected beam, discussed below.

3.5.1. The method of calculation of the displacement of the droplet based on the angular displacement of the reflected beam.

This approach is based on the formation of a collimated or close to it flow after the optical system 9, the displacements of which $\Delta l_{\text{ref}}$ are due to the angular displacement $\alpha_{\text{dis}}$ of the reflected light from the movement of the droplet, i.e., the displacement of the center of the illumination spot on the surface of the $\Delta l_{\text{dis}}$ droplet. Therefore two segments: [EE'] which is the displacement of the reflected beam with a length of $\Delta l_{\text{ref}}$ and [DE] which is the distance to the optical system 9 with a length of $l_{\text{opt}}$ are the cathets of the right triangle DEE’ (figure 3). The ratio of the first to the second is the tangent of the desired angular displacement of the $\alpha_{\text{dis}}$ or at small its values correspond to the angular displacement of the $\alpha_{\text{dis}}$ itself. So we can write:

$$\frac{|EE'|}{|DE|} = \frac{\Delta l_{\text{ref}}}{l_{\text{opt}}} = \tan \alpha_{\text{dis}} \approx \alpha_{\text{dis}} \tag{6}$$

Taking into account this formula and the angular displacement of the reflected beam from the movements of the droplet, determined by equation (5), we can obtain expression:
\[
\alpha_{m2} - \alpha_{in} = 2 \arcsin \left(1 - \frac{l_{m}}{r_{\text{drop}}} \right) - 2 \arcsin \left(1 - \frac{l_{in}}{r_{\text{drop}}} \right) = \alpha_{dis} = \frac{\Delta l_{ref}}{l_{opt}},
\]

(7)

where \( \alpha_{in} \) and \( l_{in} \) are the initial angle of reflection and the position of the center of the illumination spot on the surface of the drop, provided the following condition:

\[
l_{\text{dist}} = l_{in} - \Delta l_{\text{dis}}.
\]

(8)

For expression (7), the second term \( \arcsin \left(1 - \frac{l_{in}}{r_{\text{drop}}} \right) \) is constant, and the desired parameter is \( \Delta l_{\text{dis}} \). So equation (7) after small transformations can be rewritten to the next form:

\[
1 - \frac{l_{in} - \Delta l_{\text{dis}}}{r_{\text{drop}}} = \sin \left( \frac{\Delta l_{\text{ref}}}{2l_{opt}} + \arcsin \left(1 - \frac{l_{in}}{r_{\text{drop}}} \right) \right),
\]

(9)

And then from this expression you can derive the desired formula

\[
\Delta l_{\text{dis}} = \left[l_{in} - r_{\text{drop}} \cdot \left[1 - \sin \left( \frac{\Delta l_{\text{ref}}}{2l_{opt}} + \arcsin \left(1 - \frac{l_{in}}{r_{\text{drop}}} \right) \right) \right] \right].
\]

(10)

3.5.2. The method of calculation of the droplet’s displacement based on the linear displacement of the reflected beam.

This approach is based on focusing the optical flow after the optical system 9 so that the emerging focus is located in the middle of the AO modulator 10 in the position of the center of the AO interaction. The displacement of the droplet \( \Delta l_{\text{dis}} \) leads to focus shifts. And for certain ratios of the optical parameters of the optical system 9 and the AO mode of light diffraction this displacement of the droplet \( \Delta l_{\text{dis}} \) can be associate with the limit small displacement \( \Delta l_{\lim} \) recorded by the interference meter 5. So we can write next expression:

\[
\Delta l_{\text{dis}} = k_{dis} \cdot \Delta l_{\lim}
\]

(11)

where \( k_{dis} \) is the linear displacement coefficient.

This approach, linking the movements of the \( \Delta l_{\text{dis}} \) droplet, is simpler and will be used in the future to assess the sensitivity threshold of the JDOMS EFS.

3.6. Calculation of the sensitivity threshold of the JDOMS EFS.

When using the calculation of the displacement of the droplet based on the linear displacement of the reflected beam according to formula (11), provided \( k_{dis} = 1 \), it is possible to write \( \Delta l_{\text{dis}} = \Delta l_{\lim} \). Substituting this condition into the transformed expression (1), we obtain the desired equation for calculating the sensitivity threshold of the JDOMS

\[
E = \frac{2 \cdot v_{\text{drop}}^2}{l^2} \cdot m_{\text{drop}} \cdot \Delta l_{\text{dis}} = \frac{2 \cdot v_{\text{drop}}^2}{l^2} \cdot m_{\text{drop}} \cdot \Delta l_{\lim}
\]

(12)

For further calculations we can use the following initial data: \( v_{\text{drop}} = 1 \text{ m/s}, l_{\text{meas}} = 5 \text{ cm}=0.05 \text{ m}, l_{\lim} = 5 \cdot 10^{-9} \text{ m} \).

The value of the ratio \( \frac{m_{\text{drop}}}{q_{\text{drop}}} \), obtained on the basis of the formula of Rayleigh [8, 9, 11] for a drop of water (density of water is \( \rho = 1000 \text{ kg/m}^3 \)) with a diameter of \( d_{\text{drop}} = 1 \text{ mm}=10^{-3} \text{ m} \) with the maximum possible charge, excluding its crushing considering the fact that \( \varepsilon_0 = 8.85 \cdot 10^{-12} \frac{F}{m} \) electric constant (permittivity of vacuum), and \( a \) is the surface tension of the liquid (for water \( \sigma = 0.072 \text{ N/m} \)):

\[
q_{\text{drop}} \leq q_{\text{cras}} = \sqrt{\frac{8 \pi^2 \varepsilon_0 \sigma d_{\text{drop}}^3}{\varepsilon_0}}.
\]

(13)
And then we can get the value of the charge \( q_{\text{drop}} = 224.5 \cdot 10^{-12} \text{ Cl} \). So we can receive next
\[
\frac{q_{\text{drop}}}{m_{\text{drop}}} = \frac{6 \cdot 224.5 \cdot 10^{-12}}{\pi \cdot \rho \cdot d_{\text{drop}}^2} = \frac{6 \cdot 224.5 \cdot 10^{-12}}{3.14 \cdot 1000 \cdot (1 \cdot 10^{-3})^2} \approx 428.8 \cdot 10^{-6} \text{ Cl kg}^{-1}.
\]
Using these results and the formula (12), we get the desired value of the sensitivity threshold of the JDOMS EFS:

\[
E = \frac{2 \cdot 1^2}{0.05^2 \cdot 428.8 \cdot 10^{-6} \cdot 5 \cdot 10^{-9}} \approx 9.3 \text{ mV m}^{-1}. \tag{14}
\]

The obtained value can be refined with further studies and all the parameters of the interference meter 5, but this result show us the potential level of the developed JDOMS EFS for comparison it with similar parameters of other measuring systems.

4. Experimental result

In figure 4 shows experimentally certain schedules deviations of the trajectory of droplets with a diameter of 0.1825 mm 5% strength aqueous emulsion of the oiling agent M11, moving with velocity \( v_{\text{drop}} = 10 \text{ m/s} \) when the length plots measuring \( l_0 = 40 \text{ mm} \) (curves 1-3) and \( l_0 = 20 \text{ mm} \) (curves 4,5) formed parallel deflecting plates with a gap of 5 mm from the edges to the EFS: \( E_1 \approx 1.3 \cdot 10^6 \text{ V/m} \), \( E_2 \approx 1.0 \cdot 10^6 \text{ V/m} \), \( E_3 \approx 6.7 \cdot 10^5 \text{ V/m} \). The droplets received a charge when the voltage \( U_{\text{ch}} \) was applied to the charging electrode, varying in the range from 0 to 200 V. The M11 emulsion is similar to the Synthox-20M oiler used in the textile industry for oiling fabrics and consists mainly of dioctylsebacinate oil - 44%, genanol-08-080-R - 34 %, genanol-08-080-15% and other ingredients [9].

In figure 5 the interference signal of impulsed phase measurements generated by the photodetector 16 of the interference meter 5 is shown. It is formed by at optical flow diffraction on a running modulated USW zug (impulse) in the AO modulator 10 (according to scheme of interference measurements of the EFS on figure 2).

**Figure 4.** Experimental dependence of the displacement of the moving charged droplets under the influence of EFS (taken from [9]).

**Figure 5.** Experimental interference signal obtained in impulsed laser interferometer displacement during the light impulse in the case of diffraction on a short USW zug in AO modulator (taken from [17]).

5. The discussion of the results

1. A highly sensitive single-coordinate interference jet-drop method for measuring EFS has been developed, implemented in the JDOMS EFS, based on an electric jet generator and a impulse interference meter of droplet displacements.
2. The most sensitive method of measuring the displacement of a drop can be based on measuring the displacement of the optical flow reflected from it.
3. An increase in the light reflection coefficient from a liquid drop is possible due to the use of liquids with a dye or/and pigment.
4. Two methods have been developed for calculating the displacement of the optical flow reflected from the droplet, based on taking into account the angular or linear displacements of the beam reflected from the droplet.
5. The sensitivity threshold of the developed NEP bevel was calculated, which was ≈9.3 mV/m when using water droplets charged to the maximum value moving at a speed of 1 m/s.

6. Conclusion
1. The use of JDOMS allows to achieve high sensitivity when measuring EFS, confirming the high potential of using JDOMS EFS for various fields of science and technology.
2. The basis of the SCOIS NEP consist of two ideas:
   2.1 The use of charged moving droplets as an object sensitive to the direction and value of the EFS,
   2.2 Highly sensitive measurement of displacements of moving droplets by impaled (stroboscopic) triangulation method for recording the movements of the laser stream reflected from the droplets.
3. The implementation of three-coordinate measurements of the EFS determines theuse of three interference meters for each of their three axes X, Y, Z.
4. Increasing the sensitivity of the JDOMS EFS is possible with an increase in the ratio of the \( \frac{q_{\text{drop}}}{m_{\text{drop}}} \) due to the use of hollow drops, similar to a soap bubble, hollow metal granules and other similar techniques.

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