Electro-drop-jet microscope for active control of the surface roughness of the product

E V Leun
Lavochkin Association, 24 str. Leningradskaya, Khimki, 141402, Russia

Abstract. The article discusses questions of composition, principle of operation, two main operation modes and interrelations of the main parameters of the developed electro-jet microscope, which implements a new way of visualizing the product surface for active control of its irregularities are discussed in the article. At the heart of the device is the use of electro-jet technology to control the trajectory of the coherent monodisperse flow of transparent liquid droplets, incl. which is a coolant, serving as a focusing lens for the transmission of an optical image as in a conventional solid-state microscope. The image is recorded impulsively. One- and two-drop operation modes of the electro-drop jet microscope are presented: on the basis of a single moving drop and in the form of a combination of an ellipsoid drop oblate after impact on the surface of the article and a moving drop approaching it.

1. Introduction
Now in the rocket and space industries, machine-tool, machine-tool and instrument-making industries hydrotechnologies are actively developing, especially at the junctions of different directions. For example, optical methods and means are developed using liquid lenses used to control various parameters of optical fluxes [1, 2]. Hydraulic and drip technologies are also being improved, respectively, for processing materials and measuring the dimensions of products, as well as for the formation of monodisperse coherent droplet flow for refrigerators-emitters of spacecraft [3-5], in electro-jet jet technologies for inkjet printing, marking, dyeing and washing fibers and threads [6-10], to study the behavior of a droplet or a drop stream in electric and magnetic fields [11], studies of the nature and consequences of a drop impact on a barrier [12-17], etc. All this creates the prerequisites for expanding the scope of their application by developing methods and means of transmitting optical signals.

2. Formulation of the problem
In 2015, the author developed a hydrojet method for measuring the linear dimensions of products [18], which served as the basis for a series of subsequent studies [19-22], connected with the use of hydro-jet like a "liquid fiber" with single- and multimode light transmission modes for high-precision interference measuring the movements of the product.

However, the developed methods and devices of control do not allow realizing the visualization of the surface of the product to control its irregularities and deviations of shape. there are a number of limitations in which the use of solid-state microscopes is difficult or impossible also, for example, because of the safety requirements due to the small gap with the fast moving product during its processing, the high vibration frequency of the product exceeding the autofocusing speed of the recorder, the inability to stabilize the registrar near the mobile control zone. So the search for technical solutions and the study of drop-in microscopes in which a moving droplet or drop stream replaced the optical lens of a microscope is quite
relevant. Modern scientific research not contain such technical solutions and this article are was created to address this flaw.

3. Theory
To date, has been developed next questions: drip method to actively control the surface irregularities of the surface with drip pulse microscope (further – the microscope) for its implementation, composition, principle of operation, peculiarities of functioning. This are presented further.

3.1. Composition and principle of operation of the drip microscope
The developed microscope is shown on figure 1 and on it the product 1, the generator of drops 2, including a vibrator 3, a container with transparent liquid 4 and the calibrated nozzle 5, drops 6, a charger (device of a message unipolar charge drops) 7, rejecting device 8, control circuit 9, recorder 10, including eyepiece 11 and CCD matrix 12.

The work of microscope is considered on the example of its use for active control during processing by grinding wheel (not shown) rotating with speed $v_{prod}$ products around its axis on the grinding machine for two modes of transmission of light.

The developed microscope consist of electro-drop-jet device, similar the device represented by [8] for formation of the directed monodisperse coherent drip stream with the given trajectory of movement under an angle to a surface of the product 1 by deflecting the device 8.

So, in the capacity of 4 generator of drops 2 under constant pressure $P_{liq}$ the transparent liquid is given, for example, water, which is also coolant. On the vibrator 3, which consist of piezoelectric converter, from the first output of the control circuit 9 the alternating electric signal $U_{vibr}$, forming on a stream flowing in the mode of the laminar current from the hardened nozzle 5 diameter $d_{noz}$ is given. Growing along a stream on amplitude of oscillations, leading in the end to its forced capillary decay and drop creating mode. The condition of the flow of the laminar jet is provided by the ratio between the velocity of the jet $v_{jet}$, the diameter of the nozzle 5 $d_{noz}$ viscosity of liquid $\nu$ and the maximum value of Reynolds Re: $\frac{v_{jet}d_{noz}}{\nu} \leq Re = 2300$.

Further this jet forms a coherent stream of monodisperse drops 6 that moves straight to a surface of product 1 with speed $v_{drop}$ with the controlled sizes $d_{drop}$ in a range, at least, from 50 to 400 µm. The diameter of the
formed drops of $d_{\text{drop}}$ for the described mode of operation equals to double diameter of a jet or a nozzle: $d_{\text{drop}} \approx 2d_{\text{noz}}$.

When flown through the charger 7 drop 6 receives a controlled static charge proportional to the served from the second output of the control circuit 9 voltage $U_{\text{char}}$ with maximum value up to several kV. Moving further and flying through the rejecting device 8, the drop is deflected by the angle proportional to the amplitude of the signal $U_{\text{def}}$, coming from the third output of the control circuit 9, just as it is deflected and sent to the specified point electron in kinescope TV. Thus straightforward trajectory of movement of a drop of 6 bends.

Drops formed from a jet have small decaying oscillations in flight and it damped by force of a superficial tension and received on the surface a charge, after which take a spherical form. These moving drops perform due to the transparency of the liquid within the wavelengths of lighting $\lambda_1...\lambda_2$ function optical lens, collect reflected from the surface of the product 1 optical radiation, directing it to the recorder 10, in which the eyepiece 11 in the form of a solid lens illuminates the CCD-matrix 12, with the formation of a digital output signal $N_{\text{rec}}$ on the input circuit control 9.

Further work of a microscope is considered for one and two-drip modes of transmission of an optical stream and registration of an image (figure 2).

Single-drip mode the microscope operation is realized when approaching the surface of the product 1 spherical drop 6 on the distance equal to its focus F. In this case, the flying drop 6 and eyepiece 11 are elements of the optical scheme of the microscope.

Feature of the two-drip mode the microscope is used in the optical scheme of a microscope flying 6 and a superficial 13 drops. This last drop has the form of an hemiellipsoid (close in form to the hemisphere). It formed from hitting on the surface of the product 1 previous (or one of the previous) drop and it flattening.

**Figure 2.** Drip microscope schemes at work in one-(a) and two-drop (b) modes and accordingly optical scheme for determination of frequency of movement of drops (c) and (d).
3.2. Analysis of the main technical parameters for two modes of drip microscope operation

A large role in the developed microscope is performed by the electro-drop-jet device. And its features of the construction and modes of operation of which are already well studied in [6-10] and are used in the marking, thread dyeing and other systems. Therefore, this article is focused on the consideration of the features of impulse transmission of optical flux, registration and image, etc. provided that, as follows from [9] the maximum experimentally confirmed the diameter of the droplet, corresponding to the double diameter of the nozzle (jet) \( d_{\text{drop}} \approx 2 \cdot d_{\text{jet}} \), reached a value of 400 \( \mu \text{m} \).

3.2.1 Calculation of the maximum frequency of droplets

Due to the fact that the drop after falling on the surface of the product is an ellipsoid with a cylindrical base, the focus of the flying drop at each new measurement for the single-drip mode of the microscope should be shifted to discrete value - \( l_{1\text{min}} \) (figure 2a), which can be defined by the following formula:

\[
l_{1\text{min}} \geq 1.2r_{\text{drop}}
\]

Based on this expression, the maximum droplet frequency value \( f_{\text{drop}} \) should not exceed the next value \( f_{1\text{drop}} \):

\[
f_{1\text{drop}} \leq \frac{0.83v_{\text{prod}}}{r_{\text{drop}}}
\]

Accordingly, for the two-drip mode of operation of the microscope (figure 2b) and the formation of discrete hemiellipsoids on the surface of the product with step \( \approx l_{2\text{min}} \) we can write:

\[
l_{1\text{min}} \geq 2.2r_{\text{drop}}
\]

and

\[
f_{2\text{drop}} \leq \frac{0.45v_{\text{prod}}}{r_{\text{drop}}}
\]

Then, taking into account the above-mentioned maximum diameter \( 0.4 \cdot 10^{-3} \text{ m} \) and the standard speed of movement of the product \( v_{\text{prod}} \approx 0.6 \text{ m/s} \), swirling in the formulas (2) and (4), the frequency values of \( f_{1\text{drop}} \) and \( f_{2\text{drop}} \) should not exceed the values:

- for one-drip’s operating mode microscope \( f_{1\text{drop}} \leq 2.5 \text{ kHz} \),
- for two-drip’s mode of the microscope - \( f_{2\text{drop}} \leq 1.35 \text{ kHz} \).

3.2.2 Focus of spherical and hemispherical drops

It is known that the focal length for paraxial rays is determined by the following expressions:

- for ball
  \[
  F_{b} = \frac{R \cdot n}{2(n-1)},
  \]
- for hemisphere
  \[
  F_{hs} = \frac{R \cdot n}{(n-1)}
  \]

When used as a liquid water with refractive index 1.33 two focal lengths calculated by formulas (5) and (6), have the following values \( F_{b} \approx 403 \mu\text{m} \) and \( F_{hs} \approx 1342.3 \mu\text{m} \).

3.2.3 Features of hitting a flying drop on the surface of the product and the time of formation of the ellipsoid

The time of formation of the hemiellipsoid after impact and hitting a flying drop on the surface of the product is important for calculate of dynamic parameters during the microscope in two-drip mode and consist of the four main stages of which are shown in figure 3.

So, after hitting with a surface of the product moving spherical drops its bottom part of a drop begins to expand and liquid drops squeezed outward, occupying free space under a drop, turning of the ball (figure 3a) in a cylindrical column with hemispherical end (according to four image on the figure 3) with an edge angle equal to \( 90^\circ \).
Figure 3. The some stages of formation (a-d) of the vertical hemiellipsoid (d) from the spherical flying drop (a) after its impact on the surface.

When hitting a drop of liquid on the surface of the product, the speed range $v_{\text{drop}}$ can be divided into three subranges: low-, medium- and high-speed impact.

At slower impact of forces kinetic energy of a drop less forces of a superficial tension which are little depend on speed of movement of a drop and determine basically time of formation of superficial hemispherical drop [15].

Starting from a certain value at a medium-speed impact the kinetic energy of a drop begins to exceed the force of a superficial tension, and the speed of its movement is connected by a backward dependence with time of formation of a superficial hemispherical drop.

At further increase in the rate of impact of a drop, starting approximately from values 30-100 m/s and especially at a speed $\approx 600$ m/s leads to the fact that, its character begins to change qualitatively to the direction of clear manifestation of propagating and interacting shock waves and waves of dilution, cumulative jet and cavitation bubbles [16,17]. This will inevitably lead to diffraction, refraction and interference of the passing light significantly reducing the quality of the image of the product surface. And to exclude these nonlinear optical phenomena and taking some small reserve, it is possible to accept the maximum value of the drop speed equal to $v_{\text{max}} \approx 15$ m/s.

To understand the height of this hemiellipsoid we need to calculate the height of its cylindrical part - $h_{\text{hel}}$. So, after meeting the bottom top of the spherical drops segment (part) of the lower spherical part of the drop begins to squeezed on the sides, for formation lower cylinder with height $h_{\text{cyl}}$ and the total volume $V_{\text{cyl}} = \pi \cdot R_{d}^{2} \cdot h_{\text{cyl}}$.

After extrusion of volume of the lower segment of a hemisphere drops $V_{\text{spf}} = \frac{2\pi R_{d}^{3}}{3}$ is transformed into a cylinder by height $h_{\text{cyl}}$, i.e. volume hemisphere equals volume of the newly formed cylinder $V_{\text{cyl}}=V_{\text{spf}}$. From this ratio follows that $\pi \cdot R_{d}^{2} \cdot h_{\text{cyl}} = \frac{2\pi R_{d}^{3}}{3}$, whence it turns out that

$$h_{\text{cyl}} = \frac{2R_{d}}{3}, \tag{7}$$

and height of the extruded part of the sphere $h_{\text{sph}}$

$$h_{\text{sph}} = \frac{R_{d}}{3}, \tag{8}$$

and accordingly the time to form such a post after the start of hitting a drop on the barrier will be determined as

$$t_{\text{drop}} = \frac{h_{\text{spf}}}{v_{\text{drop}}} = \frac{R_{d}}{3v_{\text{drop}}}. \tag{9}$$

On the basis of experimental studies [15] for a water's drop with a diameter of 3 mm with the formation time of flattened hemispherical drop $t=5$ ms with the formula (9) can be determined by the formula $v_{\text{drop}} = \frac{h_{\text{spf}}}{t} = \frac{R_{d}}{3t}$. Calculating the initial value, it is possible to assume that the area of the middle speed impact $v_{\text{max}}$ begins (with some reserve) from the value $\approx 0.5... 1.0$ m/s. So it is possible to build the time dependence of the formation of the hemiellipsoid from the speed of the drop on the hard surface (figure 4).
Figure 4. The dependence of the time of formation of the vertical hemiellipsoid from the impact speed drop on the hard surface, $v_{hsi}$ – high speed impact of the drop.

Time $t_{spf}$ is determined mainly by the capillary process of interaction with the product surface, when the kinetic energy is less than the forces of surface tension

$$t_{spf} = \begin{cases} t_{drop}, & v_{msi} < v < v_{hsi} \\ \frac{r_{drop}}{3\nu_{drop}}, & v_{msi} < v < v_{hsi} \end{cases}$$

(10)

3.2.4 Calculation of the displacement point of a drop touch during its flattening and turning into an hemiellipsoid

The process of flattening drop and formation of the ellipsoid $t_{hel}$ after the beginning of contact with the surface of the moving product, the duration of which is determined by the expression (9), inevitably leads to the curvature of its shape. It is important for the two-drip mode of the microscope and determines the need to calculate the value of displacements and assessment of the criticality of this.

So during this time base of the drop shift on the value of $\Delta l_{disp}$, defined by the expression

$$\Delta l_{disp} = v_{prod} \cdot \frac{t_{hel}}{3\nu_{drop}}$$

(11)

where $r_{prod}$ is the radius of the product, $N$ - the number of turns per second.

For a drop of water diameter $d_{drop} = 400 \mu m$, moving at a speed $v_{drop} = 15 m/s$, to the product, the surface of which moves at a speed of $\approx 0.6 m/s$ and get $\Delta l_{disp} \approx 2.7 \mu m$. This is 0.6% of the diameter of the drop $d_{drop}$ and this value can be ignored.

3.2.5 Calculation of the impact force on the product surface moving water droplets

The force of impact of a moving drop in diameter $d_{drop}$ with surface of the products is described by an expression with which the majority of researchers agree [15-17]:

$$F_{drop} = \frac{\pi \cdot d_{drop}^2 \cdot v_{drop}^2}{6}$$

(12)

Calculations show that for a drop of water diameter $d_{drop} = 400 \mu m$, moving at a speed $v_{drop} = 15 m/s$, the force of impact will be $F_{drop} = 1.26 \times 10^{-3} N$. For comparison we remind that for contact methods of control of the sizes of products with intermittent surface the maximum The force of the tip at the moment of exit from a hollow on a ledge should not exceed $3 N [23-25]$. For the above calculation, the obtained value is significantly less than 1000 times and therefore the consequences of impact on the surface of the product by moving droplets of water can be ignored.

4. The discussion of the results
- The principle of action and the basic parameters of the mode of the developed electro-drop-jet microscope are presented.
- The parameters of the optical scheme of electro-drop-jet microscope for one- and two-drip modes of operation are presented.
- Range of values for impact drop with middle speed of water about a hard surface utilization from $\approx 1.0$ to $15.0$ m/s is defined. This range corresponds to the following two conditions:
  - minimum time of formation a liquid hemiellipsoid from a spherical flying drop after its impact on the surface;
  - absence of nonlinear phenomena similar shock waves and waves of dilution, cumulative jet and cavitation bubbles.
- The features of the impact of a flying drop on the surface of the product are considered and the time of transformation of a spherical drop into an hemiellipsoid is calculated.
- The consequences of displacement of the point of touch of the flying drop during its flattening and transformation into the hemiellipsoid are considered. It is shown that for water drop with diameter $d_{drop} = 400$ µm, moving at the speed of $v_{drop} = 15$ m/s to the product, the surface of which is moved at a speed of $v_{prod} = 0.6$ m/s and the obtained value $\leq 2.7$ µm and about 0.6% of the diameter of the drop and this value can be ignored.
- Calculated the force of impact on the product surface drops of water diameter $d_{drop} = 400$ µm, moving at a speed $v_{drop} = 15$ m/s. This value was $d_{drop} = 1.26 \cdot 10^{-3}$ N and it can be ignored.

5. Conclusion

The new class of measuring devices is developed – electro-drop-jet microscope, realizing impulse way of visualization and active control of irregularities of a product surface. This electro-drop-jet microscopes based on theoretical and experimental electro-drop-jet technology combined with a new direction associated with the use of coherent drip flow fluid to transmit and measurement of optical fluxes. The article presents the first results of its theoretical researches and opens a series of scientific publications on this topic.

6. References

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