

INVESTIGATION OF THE EVOLUTION OF THE SPECTRUM OF OSCILLATIONS OF THE SURFACE OF A JET OF LIQUID WITH FORCED CAPILLARY BREAKUP

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The results of an experimental study of the spectral composition of the surface oscillations of a jet of liquid at different distances from the point of efflux from the head of the apparatus which produces forced capillary breakup of fluid jets are presented.

In the great majority of experimental investigations of forced capillary breakup of liquid jets (FCBJ) primarily the linear stage of breakup is still being studied. This stage is described quite well by Rayleigh's model of capillary breakup of an infinite liquid cylinder [1]. However many physical effects which accompany FCBJ and are important for practical applications cannot in principle be understood on the basis of the linear theory [1]. These include primarily the production of satellite drops, i.e., very small drops which are produced together with the main drops in FCBJ, in some breakup regimes. It is understandable that satellites hinder the normal operation of jet-drop printing and marking devices, they significantly degrade the monodispersity of metallic and ceramic microgranules obtained by means of cryodispersion technology [2], etc.

The large number of theoretical works on the mechanisms of satellite-drop formation and the nonlinear stages of FCBJ (see, for example, [3-5]) does not compensate for the sparsity of experimental information, virtually all of which is contained in [6-8], in this field.

In this work we make a significant addition to existing experimental data on nonlinear effects accompanying FCBJ by studying the evolution of the spectrum of surface oscillations of a jet along the Z axis, which is also the symmetry axis of the jet. The origin of coordinates is located at the point of efflux from the head of the FCBJ apparatus.

A block diagram of the experimental apparatus is shown in Fig. 1. The method consists of recording with the help of an optical multichannel analyzer (OMA) the images of a section of the jet illuminated with coherent radiation. In the process, with the help of a delay line the signal at whose input was synchronized with the signal of the master oscillator, the phase of observation was systematically varied from 0 to  $2\pi$ . The images, obtained in this manner with the help of the OMA, of the "cutoff" of the jet in different phases were fed through a CAMAC interface into an IBM PC AT computer, where the spectral composition of the oscillations was determined. The spectrum of the surface oscillations of the jet at different distances from the efflux channel, i.e., the evolution of the spectrum along the Z axis, was determined by moving, with the help of a micrometric screw, the FCBJ apparatus relative to the optical axis of the recording system. The spectra of the master oscillator signals and the dynamic pressure in the chamber of the FCBJ generator were measured simultaneously with the help of a fast analog-to-digital converter in the CAMAC system and a semiconductor pressure gauge, which were connected to the PC.

The optical multichannel analyzer employed for recording an enlarged image of the "cutoff" of the jet is constructed based on a 1200TsL2 linear CCD array which contains 2048  $15 \times 15 \mu\text{m}$  photosensitive elements and CAMAC electronic modules, which control the operation of the CCD array, accumulation of information, rapid conversion of information into a digital code, and transmission to the PC for processing [9]. The source of coherent radiation was an argon laser of the type GLN-502 and an acousto-optic modulator, which modulates the laser radiation synchronously with the signal of the master oscillator. As mentioned above, the phase of the synchronization pulses was varied with the help of a delay line within the period of the master-oscillator signals.

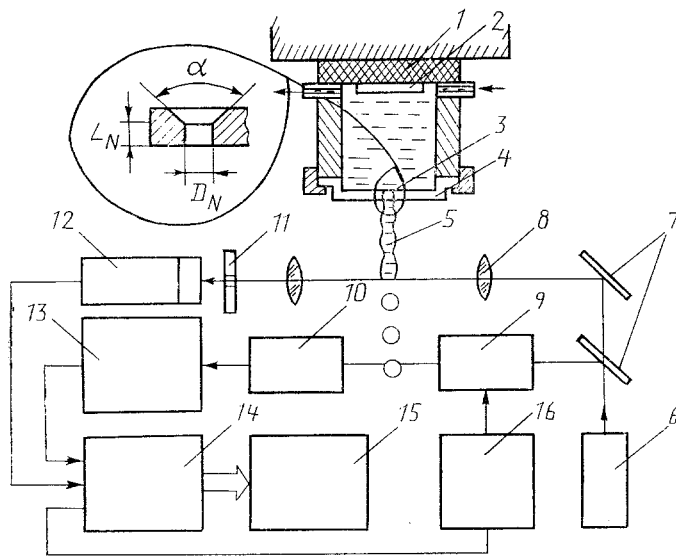


Fig. 1. Diagram of experimental apparatus for studying FCBJ: 1) body of the FCBJ apparatus; 2) piezoelectric vibrator; 3) jet efflux channel; 4) nozzle head; 5) unbroken part of the jet; 6) laser; 7) mirror; 8) lens; 9) acoustooptic modulator; 10) electro-optic transducer; 11) diaphragm; 12) photomultiplier; 13) optical multichannel analyzer; 14, 16) CAMAC moduli; 15) microcomputer.

Automatic image processing was performed with the help of the methods developed on the basis of the linguistic approach to the theory of image recognition. Every image was analyzed, after preliminary correction (removal of unimportant "spikes" and "dips"), in a fixed space of indicators. In the general case the presence of any particular indicator indicates that the image contains a definite geometric feature. After such analysis the structure based on which the parameters were determined was chosen in accordance with a deciding rule. In those cases when the type of image analysis described above was impossible to perform (the image was extremely irregular and the decision rule singled out several equivalent structures) the parameters were determined visually. In both cases the data were stored, after processing, in a data file for subsequent analysis.

A Fourier analysis of the obtained tabulated periodic function was performed for every experimental point on the  $z$  axis. An expansion in a Fourier series of the form

$$D(t) = D_0 + \sum_{k=1}^M D_k \sin(k\omega_0 t + \varphi_k)$$

was employed. Here  $\omega_0$  is the cyclic frequency of the excitation signal and  $D_k$  and  $\varphi_k$  are the amplitude and phase of the harmonics of the oscillations of the diameter of the excited jet. For  $M = 4$  harmonics it gave an rms error of not more than 0.5% of  $D_0$ .

The basic experimental results obtained in this work are shown in Fig. 2. Figure 2a shows on a semilogarithmic scale the  $Z$  dependence of the ratio  $\delta/R$  for a weak initial disturbance  $\delta_0$  of a water jet with harmonic excitation and the optimal dimensionless wave number  $\kappa = \pi D_j / \lambda = 0.69$ . Satellite formation was not observed in this case. The value of the dimensionless rate of buildup  $\gamma_* (\delta = \delta_0 e^{\gamma_* \tau_d}, \text{ where } \tau_d = L_j / v_j \sqrt{8\sigma / \rho D_j^3}) (\gamma_* = 0.34)$ , measured from the slope of the straight line  $\ln(\delta/R) = Fu(Z)$ , is close to the value obtained on the basis of Rayleigh's theory. A characteristic feature is rapid buildup (with a rate that is three to five times higher rate than for the excitation frequency) of the amplitudes of the higher-order harmonics that occurs near the region where the jet breaks up into drops.

When a jet is excited under analogous conditions ( $\kappa = 0.69$ , unimodal excitation, no satellites) by a large-amplitude signal the character of the evolution of the spectrum of oscillations changes significantly (see Fig. 2b). The characteristic regions can be clearly seen on the obtained curves: the first region, which extends from the exit from the head up to  $z_1 = (3-5) \cdot D_N$ , is associated with the conversion of oscillations of the pressure and velocity of the liquid in the FCBJ apparatus into oscillations of the surface of the jet; the second region,  $z_1 < z < z_3$ , is associated with the linear stage of breakup ( $\gamma_* = \text{const}$ ); and, finally, the third region,  $z > z_3$ , is associated with the nonlinear stage of breakup, characterized by a rapid increase of the buildup rate  $\gamma_*$ . An important feature of the obtained results is that the buildup rate  $\gamma$  in the linear region is different from the value predicted by Rayleigh's theory; this agrees with the experimental results of [8]. This means that for an initial large-amplitude excitation the FCBJ cannot be explained by Rayleigh's theory at any stage. Finally, for FCBJ, corresponding to far from optimal values of  $\kappa$ , the

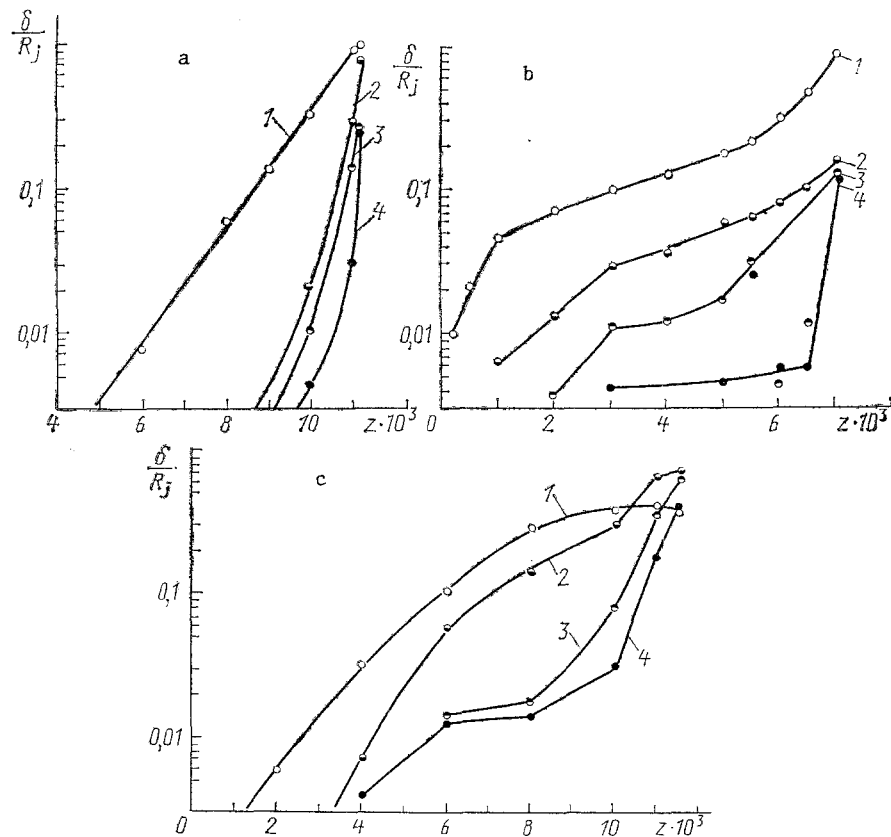


Fig. 2. Relative amplitude  $\delta/R_j$  of the disturbances of the jet surface as a function of the coordinate along the jet  $z$  [ $\alpha = 0.69$  (a), weak excitation;  $\alpha = 0.69$  (b), strong excitation;  $\alpha = 0.35$  (c), strong excitation]: the curves 1-4 correspond to the frequencies  $\nu_0$ ,  $2\nu_0$ ,  $3\nu_0$ , and  $4\nu_0$ , respectively.  $Z$  is given in meters.

spectrum of oscillations of the jet contains a significant admixture of harmonics whose amplitude near the breakup region often exceeded the amplitude of the signal at the excitation frequency. Thus Fig. 2c shows curves of  $\delta/R$  versus  $Z$  in the case of unimodal excitation and  $\alpha = 0.35$ . In this case satellite formation was observed.

#### NOTATION

$D(t)$ , diameter of the jet of liquid being dispersed;  $R = D/2$ , the radius of the jet;  $\omega_0$ , cyclic frequency of excitation;  $D_k$  and  $\varphi_k$ , amplitude and phase of the oscillations of the surface of the jet in FCBJ at the frequency  $k\omega_0$ ;  $\delta$ , amplitude of the perturbations of the jet;  $\delta_0$ , amplitude of the initial perturbations of the jet [ $\delta_0 = \delta(Z = 0)$ ];  $D_N$ , diameter of the efflux channel;  $D_j$ , diameter of the undisturbed jet;  $L_j$ , length of the unbroken part of the jet;  $\lambda = 2\pi v/\omega_0$ , wavelength of the excitation;  $\alpha = \pi D_j/\lambda$ , dimensionless wave number;  $\tau_d$ , dimensionless breakup time;  $\gamma_*$ , dimensionless rate of buildup of the disturbances of the jet;  $\sigma$ , surface tension; and  $\rho$ , density of the dispersed liquid.

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