

Break-up of a Liquid Jet Induced By Non-Sinusoidal Perturbations

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Abstract

This study reports the results of an investigation on the break-up of viscous jets submitted to multimode piezoelectric stimulations. This is performed by modulating the exit velocity with non-sinusoidal perturbations. Previous experiments carried out with this type of stimulation have been limited in finding acceptable configurations for break-up essentially with the help of stroboscopic photographs of the jet behaviour. The spatial information obtained from analyses of photographs proves to be only sufficient to give tendencies. Temporal information is required to study the correlations between the satellite formation and the excitation imposed on the jet, and as demonstrated in this paper may be useful for testing theoretical models. In this work, we perform non-sinusoidal piezoelectric excitation experiments for various values of voltages and phase angle under stable and unstable conditions. The cases studied also include in-phase and out of phase superimposition of fundamental and overtones. Spectral analysis used in conjunction with a laser photometric method unveils the interactions between the fundamental and the harmonic components which grow at different rates and determine the final behaviour of the jet. In particular, we show how the non-linear interaction between the fundamental and the harmonics may be ascribed to the formation of a variety of dropsizes and shapes.

Introduction

Continuous ink-jet technology requires the formation of calibrated drops, from a jet, at a well defined rate. With fluids of rather low viscosity such as those used in continuous ink-jet printing, all techniques which result in a sinusoidal stimulation of low amplitude of the jet lead to break-up with satellites which are deleterious for printing, unless properly controlled, since they lead to drop placement errors.

It is possible, imposing a complex periodical signal to obtain a stream of drops devoid of satellites. This has been successfully demonstrated for piezoelectric excitation,[1,2] for the electrohydrodynamic stimulation technique,[3,4] and the thermal disturbance of the jet.[5]

The latter two above cited methods are free from nozzle interactions[6] but unfortunately, cannot provide with large perturbations of the jet such as those used in this investigation.

As stated earlier, a practical method of eliminating the formation of the satellite drops is by using a modulated disturbance. In terms of piezoelectric stimulation, Chaudhary and Maxworthy[1], as well as Scheller and Bousfield[2] provide results of such experiments. However these authors limit their experimental investigation to stroboscopic visualization and are thus unable to provide quantitative information on capillary wave dynamics which control jet break-up.

In this work, we report results obtained for various multimode piezoelectric stimulation cases using both the stroboscopic technique for measuring break-up lengths and a laser photometric device combined with spectral analysis. The latter method has been shown to be adequate for non-intrusive measurements of the jet surface profile[6]. The processed signals allow to recover the amplitudes of the different Fourier modes and the phase shifts of the harmonics relative to the fundamental. This enables us to pinpoint the differences in the development of an initial disturbance applied to the jet and thus to propose a method capable of evaluating in a quantitative manner performances of various waveforms in terms of jet break-up. Finally, the spectral analysis of the experiments proves to be invaluable for comparisons with non-linear theories[7].

Experimental

Jet Generation and Stimulation

The piezoelectric stimulation technique essentially consists of a fluid chamber comprising an acoustic transducer at one end and a nozzle at the other.

Temperature controlled fluid is supplied from a pressure-regulated reservoir to the fluid chamber. A vertical jet issues from a 70 μm diameter nozzle which has a length over diameter ratio of about one.

The acoustic transducer is made of a piezoelectric ceramic bonded to a steel rod. The expansion and contraction of the piezo ceramic-rod assembly within the fluid chamber varies its volume behind the nozzle, allowing a velocity perturbation to be applied onto the jet issuing from the nozzle. Since the volume of the fluid chamber is small, we can assume that the pulsation input from the transducer motion is completely transferred to the jet.

This perturbation is then amplified along the jet and leads to drop break-up. Jet break-up either in presence or absence of satellites could be obtained by this technique[6]. Other details are shown on figure 1.

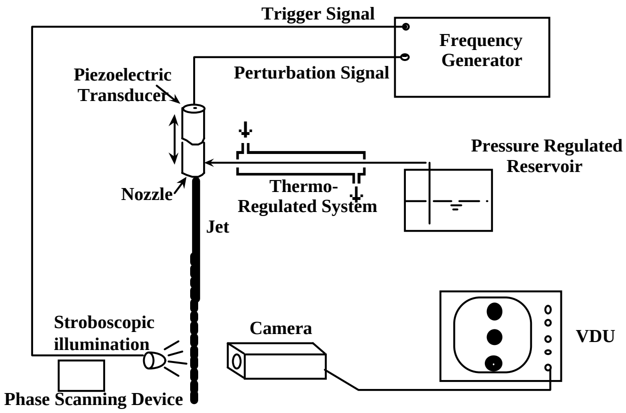


Figure 1. Schema of the experimental set-up

Our study is limited to the effect of the second harmonic. So the voltage to be fed to the transducer should contain the sinusoidal waveform and the second harmonic. This signal is synthesized on a microcomputer using several dozens of data points for one period. The modulated waveform is then sent to the arbitrary frequency function/amplifier generator. Then the digital signal is converted to analog and amplified to drive the piezoelectric crystal with a periodically varying voltage comprised between 1 and 200 volts peak to peak.

The jet's exit velocity modulation can be assumed to be of the following form:

$$u = u_1 \sin(\omega t) + u_2 \sin(2\omega t + \varphi) \qquad (1)$$

where u_1 and u_2 are the amplitudes of the fundamental and the second harmonic velocity contributions respectively, $\omega = 2\pi f$ is the angular frequency with f being the fundamental frequency and finally φ is the phase angle between the fundamental and the second harmonic.

Since we are using the transducer at various frequencies, it is necessary to know its behaviour over a large range of frequencies. This is shown in figure 2 for an excitation voltage of 200 Volts.

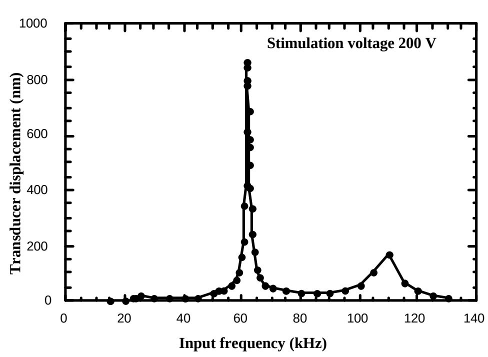


Figure 2. Transducer displacement versus frequency

This result has been obtained at ambient pressure using a laser vibrometer which measures the surface motion of the piston using interferometric techniques. One can notice that the resonant frequency under these conditions is between 62 and 63 kHz whilst the second harmonic of the transducer is around 110 kHz. There might be a slight shift in resonant frequency and probably also a change in the amplitude of vibration when the transducer is submitted to pressure i.e. under flow conditions. Due to various difficulties associated with the experiment (very small orifice, light rays on the same path as the jet) it has not been possible to measure the characteristics of the piezoelectric transducer under actual working conditions. Since the rigidity of the resonator is very high, it is reasonable to assume that the overall behaviour should remain the same.

According to figure 2, it appears that the behaviour of the transducer will be the same from around 40 to 55 kHz and then on from 70 to 100 kHz. So it is necessary to choose appropriately the working frequencies and/or the excitation voltages.

Measurement Techniques

The first measurement technique to be discussed, is the stroboscopic visualization of the jet. For this purpose, we use the arbitrary frequency generator cited above to also drive an LED which helps to capture still images of jet break-up. A phase scanning device set in-between the generator and the LED allows to introduce a variable phase shift between the transducer triggering signals and those of the LED[6] and thus to strobe the jet at different relative times.

The second measurement technique used in this study, is the laser shadow method which allows to perform non-intrusive measurements of the jet surface profile. This extremely accurate technique which has the capability to resolve relative diameter variations as small as 10^{-3} has been discussed in an exhaustive manner elsewhere[8] and therefore only the main features necessary for the understanding of the results given in the next section will be presented here. The main components of the measuring system are a laser diode and attendant optics which shape the beam into a thin laser sheet. In the course of the experiment during which the jet is slowly displaced in front of the light, the sheet is cut by the opaque jet. The transmitted light which gives the jet profile is then projected onto a photodiode. The signal collected by the photodiode is amplified before being sampled using a digital oscilloscope and sent to a micro-computer. A Discrete Fourier Transform (DFT) procedure is used to expand the jet radius into Fourier modes and to extract information on both amplitudes of different modes and phase shifts between the fundamental and the harmonics.

Results and Discussion

Break-up length and spectral measurements are performed at various excitation voltages and phase angles under different operating conditions. Stroboscopic photographs are also taken at the late stages of the jet. The ink used in the experiments has a viscosity η of 4.4 mPa.s, a density ρ of 1172 kg/m^3, and a static surface tension σ_s of 50 mN/m.

Multimode Stimulation Break-up Mechanisms

For our purposes, we consider an axisymmetric jet emanating from a nozzle of radius R_0. The jet travels at a velocity V_0 which is much greater than the characteristic capillary speed $V_c = (\sigma/\rho d)^{1/2}$ and is perturbed by a modulated velocity (see equation 1) with a frequency f of wavelength λ .

The theoretical temporal analyses of capillary jet break-up demonstrate that for small initial perturbations, the cut-off dimensionless wavenumber

$$k_c = \frac{2\pi R_0}{\lambda}$$

is close to 1. Disturbances larger than one should not grow. This is specially important when superimposition of two different wavenumbers isused to disturb the jet. For instance, if both wavenumbers are below the cut-off wavenumber, they both will grow (unstable condition for the second harmonic) and if one is below and the other is above the cut-off wavenumber (stable condition for the second harmonic), the smaller one will grow and the larger one will oscillate.

Stable Second Harmonic

We choose to discuss in this sub-section the following cases. First a jet subject to an initial perturbation consisting only of the fundamental and then, the fundamental and an added stable second harmonic.

The first experiment is performed at k = 0.69 (most unstable wavenumber) with only a sinusoidal signal. This gives rise to a velocity contribution which at the nozzle exit leads to an initial dimensionless radius perturbation also called input hereafter of the order of 0.01.

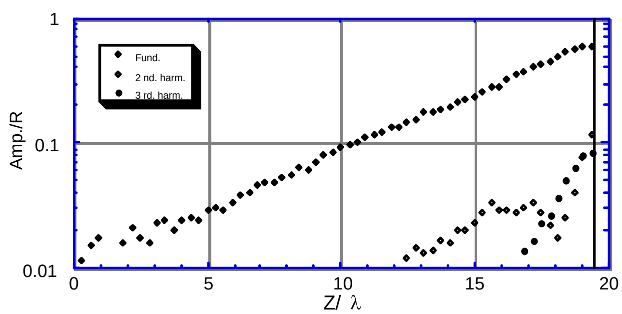


Figure 3. Normalized amplitudes of fundamental and harmonics for k=0.69 and sinusoidal stimulation signal

The results for this experiment are shown on figure 3 where for the sake of legibility we have plotted only the growth of the fundamental and the second and third harmonics. The growth of the fundamental is close to exponential as expected from linear theories and the overtones begin to grow during only the last quarter of the jet life.

The second experiment is again performed at k = 0.69.

This time, the second harmonic added to the fundamental. Both initial inputs are of the order 0.01 in order to compare with the theoretical results based on the numerical solution of the Navier-Stokes equations for the problem at hand by Huynh et al[7]. The addition of a stable second harmonic component is exemplified on figure 4 where it is seen growing with a slope equal to that of the fundamental up to a dimensionless length of about 5 Z/λ from the nozzle. The growth of the second harmonic then suddenly breaks down before beginning to oscillate with some damping. This latter behaviour is close to the theoretical predictions[7].

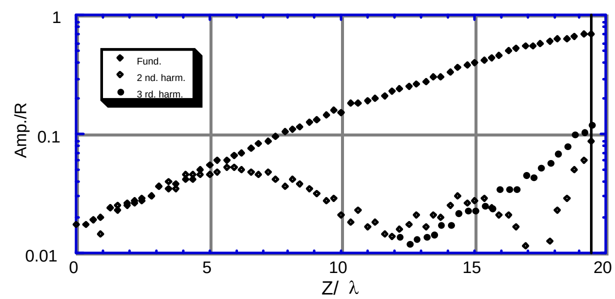


Figure 4. Multimode stimulation for k=0.69. Growth of fundamental and harmonics

We can also see by comparing figures 3 and 4 that the addition of the second harmonic has no major influence on the jet intact length since the break-up lengths represented by the vertical lines are the same for both experiments.

Unstable Second Harmonic

In this sub-section we consider the three following cases. Fundamental input only, and then fundamental with second harmonic either with a phase angle φ of 0° or of 180°. According to the indications given above, it is necessary to choose the fundamental such that the second harmonic can be amplified, so the dimensionless wavenumber constructed with the fundamental should be smaller than 0.5.

We show on figure 5 the growth of the fundamental and the second and third harmonics for an experiment performed at k = 0.45 with a sinusoidal input.

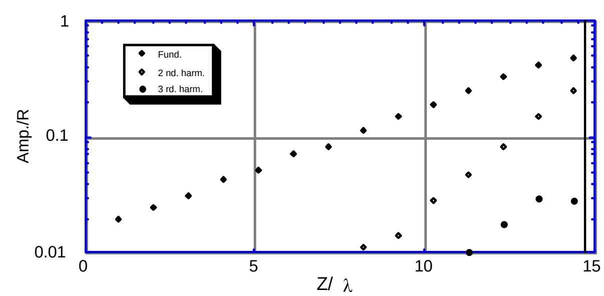


Figure 5. Normalized amplitudes of fundamental and harmonics for k=0.45 and sinusoidal stimulation signal

We can note that the growths of the fundamental and the second harmonic are close to exponentials with a steady growth for the second harmonic and a slope equal to almost two times that of the fundamental.

The second case is again for k = 0.45 with the second harmonic added to the fundamental with a phase angle of 0°. Both initial inputs are at 0.01, again for the purpose of comparison with theoretical results[7]. In contrast to the results of the stable second harmonic (figure 4), one can note on figure 6 that the growth of second harmonic is steady up to break-up of the jet with almost no difference with the fundamental. Notice also that in contrast to the former case that the break-up time is drastically reduced (almost one third) when using an unstable second harmonic. The comparisons with the theoretical results[7] are good over the major part of the jet but deteriorate during the very late stages of the jet. In particular, the similarity in the growths of the fundamental and second harmonic that is noticed experimentally in figure 6is not well described.

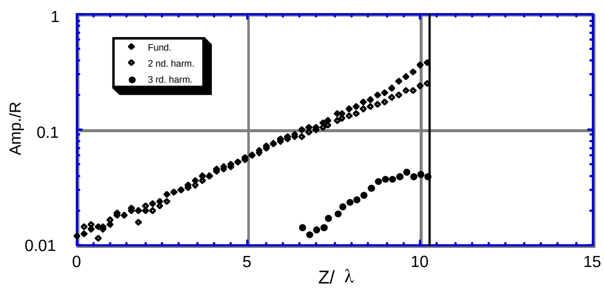


Figure 6. Multimode stimulation for k=0.45 and φ=0°. Growth of fundamental and harmonics

The third experiment is carried out at k = 0.45 with the second harmonic added to the fundamental with a phase angle of 180°. Both initial inputs are again at 0.01.

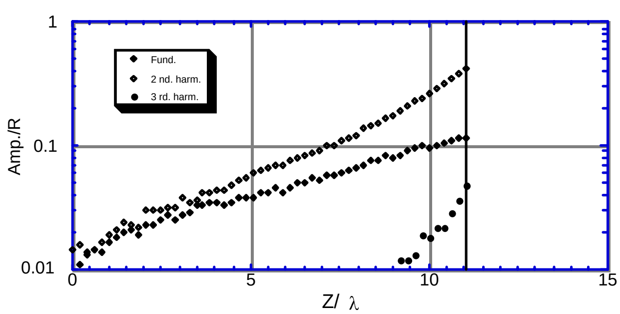
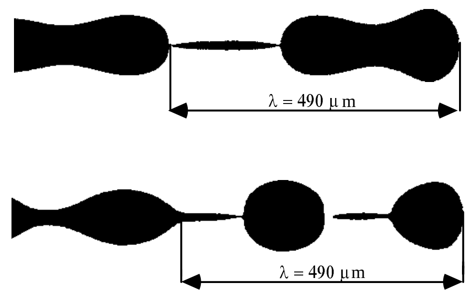


Figure 7. Multimode stimulation for k=0.45 and φ=180°. Growth of fundamental and harmonics

In contrast to the above case, the second harmonic overtakes the fundamental in the early stages of the jet life as demonstrated on figure 7 and seems to control completely the outcome of the break-up. This result is in discrepancy with the numerical simulations of Huynh et al[7].

Finally in figures 8a and 8b we give the stroboscopic photographs of the jet for the experiments performed at k=0.45and φ= 0° and 180° respectively.

The contractions and the bulgings which are observed are very different from one case to the other. Indeed, on figure 8a, the wavelength at the time of break-up includes a large drop and a large satellite, whilst figure8b shows that for φ = 180° the break-up occurs almost simultaneously with two drops and two small satellites. This is in correlation with figure 7 where the ratio of second harmonic to fundamental is higher. Finally these figures illustrate the fact that a variety of drop sizes can be obtained by modulated jet break-up.



Figures 8a and 8b. Stroboscopic photographs at break-up for different operating conditions

Conclusions

In this paper, we have performed an experimental investigation of the effect of multimode piezoelectric stimulation on the break-up of a liquid jet. For this purpose, we have used excitations with and without the second harmonic. The cases studied include stable and unstable conditions with in-phase and out of phase superimposition of fundamental and overtone. Various measurement methods including stroboscopic visualization and spectral analysis have been used.

The stroboscopic illumination allows to obtain photographs representing the characteristic shapes of drops and satellites but is unable to provide any information on the capillary wave dynamics which lead to a variety of drop break-up patterns.

The laser shadow technique used in conjunction with DFT analysis allows to extract values of the amplitudes and phase shifts of harmonics from the temporal variation of the jet radius. This method proves to be invaluable in characterizing the intricate surface phenomena and in testing the validity of numerical simulations. It is important to emphasize that this type of comparison is unique and has not yet been reported in the literature.

Finally to summarize, we can conclude that the addition of the second harmonic under stable conditions has negligible influence on the break-up lengths, although the initial value of the second harmonic may have some effect on the nature of the satellite. In contrast, under unstable conditions, the second harmonic controls the break-up. Moreover in the latter case, the phase shift between the fundamental and the harmonic disturbance has a large effect on the break-up location and by the way on the size of the drops and satellites.

References

1. K. C. Chaudhary and T. Maxworthy, *J. Fluid Mech.* **96**, 287, (1980).
2. B. L. Scheller and D. W. Bousfield, *Chem. Eng. Comm.* **107**, 35, (1991).
3. I. Rezanka and J. M. Crowley, *J. Imaging Sci. and Technol.* **16**, 1, (1990).
4. B. Barbet, P. Atten and A. Soucemarianadin, *J. Imaging Sci. and Technol.* **41**, 570, (1997).
5. B. Barbet, P. Atten and A. Soucemarianadin, Proc. IS&T's XIIIth Intl. Cong. on Advances in Non Impact Printing Technol. 604, (1997).
6. B. Lopez, A. Soucemarianadin and P. Attané, Proc. IS&T's XIIIth Intl. Cong. on Advances in Non Impact Printing Technol. 609, (1997).
7. H. Huynh, N. Ashgriz and F. Mashayek, *J. Fluid Mech.* **320**, 185, (1996).
8. J. Xing, A. Boguslawski, A. Soucemarianadin, P. Atten and P. Attané, *Exp. in Fluids* **20**, 302 (1996).

Acknowledgments

The authors extend their appreciation to the Région Rhône-Alpes for partially funding this work through a research grant.

Biography

Arthur Soucemarianadin is Professor of Mechanics at the University Joseph Fourier in Grenoble, France, where he is with the Laboratory of Rheology. His current research interests include the study of rheologically complex fluids submitted to acoustic, electrical and/or thermal fields. He is the author of numerous scientific and technical papers and holds 6 patents relating to petroleum engineering processes and printing equipments. He is a member of IS&T and the American Society of Rheology.

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