Experimental Study of the Transmission of Acoustic Waves to a Liquid Jet Emerging from a Reservoir

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Abstract

The transmission of a periodic disturbance to a liquid jet emerging from a drop generator is governed by the acoustic field set up within the liquid reservoir and the geometry of the nozzle from which the jet emerges. This paper describes experimental data for pressure disturbances within a drop generator resulting from applied acoustic waves.

Introduction

The breakup of a liquid jet into discrete drops can be controlled by the application of a periodic disturbance to the jet. Linear stability theory [1] predicts that the disturbance will grow exponentially and break the jet into drops provided the disturbance wavelength is greater than the jet circumference.

Various methods are used for imposing the disturbance on the liquid jet [2,3,4,5]. In most cases, a frequency generator drives a piezoelectric crystal to transmit the vibration to the liquid jet as it emerges from a nozzle. Many devices have the piezoelectric crystal mounted directly to the nozzle [6], physically vibrating the nozzle as the liquid emerges. In the production of molten metal jets in this laboratory, an alternative arrangement is used in which the piezoelectric crystal transmits vibrations to the liquid contained in a reservoir chamber above the nozzle.

If the jet is electrically charged, then the drops can be deflected by an electric field placed at the point where the jet breaks into drops. In order to achieve uniform deflection properties, the distance from the nozzle at which the jet breaks up into drops must be carefully controlled. This breakup length varies with the magnitude of the initial disturbance amplitude applied to the jet. If $\alpha$ is the temporal exponential growth rate of the applied disturbance and $\eta_0$ is the initial disturbance amplitude as the jet emerges from the nozzle, then the breakup length is given by

$$l = \frac{u}{\alpha} \ln \left( \frac{a}{\eta_0} \right)$$  \hspace{1cm} (1)

for a jet of radius $a$, moving at uniform velocity $u$.

For a constant breakup length, it is important to be able to maintain a constant initial disturbance amplitude at the nozzle. This is the motivation for measuring the magnitude of the pressure disturbances at the nozzle of a drop generator.

In this paper we present experimental results of the magnitude of the acoustic pressure amplitude within the reservoir chamber and at the nozzle exit of a drop generator. A simple one-dimensional model of a standing wave is used to describe the acoustic field in the chamber and the nozzle. The model can be used to predict the effect of applied disturbance frequency and level of fluid in the reservoir on the disturbance amplitude at the nozzle.

Experimental Description

Figure 1 shows the drop generator. It consists of a pressurized liquid reservoir chamber and nozzle used to produce a jet of fluid with an imposed disturbance.

The chamber is 6 cm internal diameter. Liquid fills the chamber to a height of 15 cm. A PZT crystal is mounted at the base of a hollow cylindrical plunger which is immersed in the reservoir fluid. The PZT is driven by a frequency generator and transmits vibrations through a thin metal diaphragm to the fluid. The base of the plunger is positioned close to the entrance of a nozzle which leads to the orifice from which the liquid jet emerges. The chamber is pressurized with nitrogen gas to drive the liquid through the nozzle. The height of liquid in the chamber can be maintained by continuous feed of liquid to the chamber. The liquid used in the experiments was propanol for room temperature testing.

To measure the acoustic pressure field, a pressure transducer (Kistler Model 6013B) was attached (a) flush with the base of the reservoir chamber and (b) at the exit of the nozzle. In the former case, the pressure transducer was able to measure the pressure field in the reservoir chamber alone and in the latter case the acoustic field

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transmitted through the nozzle to the orifice was measured. The signal from the pressure transducer was amplified and monitored with a HP35665A Dynamic Signal Analyzer.

![Diagram of the Drop Generator Apparatus](image)

**Figure 1.** Drop Generator Apparatus. Liquid Reservoir and Nozzle Assembly.

In a typical experimental run, the liquid level in the reservoir chamber was held constant while the frequency applied to the PZT crystal was swept between 1 and 30 kHz, to cover the range of frequencies used in the drop generator.

Figure 2 shows a plot of the variation in acoustic pressure at the base of the reservoir chamber at two different applied frequencies. The liquid level in the chamber is varied from 2 cm to 11 cm above the chamber base. The spatially periodic signal response indicates the presence of an acoustic standing wave in the reservoir chamber. The wavelength of the standing wave is given by the acoustic velocity in the liquid divided by the applied frequency. Peaks in the signal response occur at half-wavelength intervals.

Figure 3 plots the acoustic pressure against applied frequency at two fixed liquid levels. Standing waves appear at harmonics of the fundamental frequency at which the height of the liquid in the reservoir equals one half-wavelength.

Figure 4 shows a contour plot giving the magnitude of the pressure amplitude at the base of the reservoir chamber as a function of both applied frequency and liquid level. The peak pressure levels trace curves in the contour plot corresponding to standing wave patterns.

![Acoustic pressure measurements](image)

**Figure 2.** Acoustic pressure measurements at the base of the fluid reservoir. Applied frequencies of 16 kHz and 30 kHz.

![Pressure amplitude plots](image)

**Figure 3.** Acoustic pressure measurements at the base of the fluid reservoir. Liquid heights 4 cm and 8 cm.

The position of the plunger was adjusted to different heights above the chamber base. Figure 5 shows plots of pressure amplitude at a fixed applied frequency with the plunger 2 cm and 6 cm above the base of the chamber. Apart from a drop in the magnitude of the pressure amplitude when the
plunger is moved away from the pressure transducer, the wavelength of the standing wave remains constant.

When the pressure transducer is placed at the nozzle exit, separated from the chamber by the small diameter entrance length of the nozzle, the recorded pressure field changes markedly. Figure 6 shows the contour plots of pressure measurements from two nozzles of identical diameter but different entrance lengths. In each case, the background standing wave pattern in the chamber is evident, but there is a strong attenuation of the pressure waves by the nozzle at all frequencies except for two narrow frequency bands where the pressure wave is enhanced above that of the background standing wave.

**Theoretical Description**

The experimental results give the amplitude of pressure waves imposed on a liquid jet emerging from the orifice of a drop generator. The pressure amplitude is governed by the acoustic field within the liquid reservoir, the height of liquid in the reservoir and the characteristic length of the exit nozzle.

A complete explanation of the acoustics in the drop generator would be based on the three dimensional solution for a standing wave in an annular cylindrical geometry. However, to a first approximation, we can apply a simple one-dimensional analysis of standing waves in a tube with forced vibrations at the base of the liquid column and with a free interface with gas at the top of the liquid column. The height of the liquid column can be varied and there is full reflection of acoustic waves at the liquid-gas interface.

Standing waves are formed when incident and reflected waves coexist. Superposing two waves propagating in opposite directions:

\[ p(x, t) = p_0 \sin(kx - \alpha t) + p_0 \sin(kx + \alpha t) \]

\[ = 2p_0 \sin kx \cos \alpha t \]  

**(2)**
The resulting expression represents an oscillation of temporal frequency $\omega$ with a finite spatial extent determined by the spatial frequency $k$. For example, in a column of length $L$, if one end of the column is closed (e.g. liquid-gas interface) and the other end is forced, $p(0,t) = 0$ and $p(L,t) = 2p_0 \cos(\omega t)$, so:

$$\sin(kL) = 0$$

or

$$kL = (2n-1)\frac{\pi}{2} \quad \text{for} \quad n = 1,2,\ldots$$

(3)

or

$$\lambda_n = \frac{2\pi}{k} = \frac{4L}{2n-1} \quad \text{for} \quad n = 1,2,\ldots$$

which represent the wavelengths of allowed standing waves in the fixed column length $L$.

The corresponding harmonic frequencies of acoustic waves, travelling at speed $c$ in the column will be given by:

$$f_n = \frac{c}{\lambda_n} = \frac{(2n-1)c}{4L}$$

(4)

If $L$ represents the liquid height in the reservoir chamber, then a series of curves can be drawn of $L$ versus frequency $f_n$. These curves are the solid lines plotted on the contour plots of the experimental data in Figure 3 for a value of the acoustic velocity in propanol $c = 1050$ m/s.

The simple one-dimensional analysis of the standing wave pattern in the reservoir is in close agreement with the experimental results. The experimental data also show secondary peaks along the standing wave contours. These are presumably the result of the more complex three dimensional standing wave pattern set up in the chamber with incident and reflected waves from the liquid surface, the chamber and tube walls all superposed.

The effect of the nozzle entrance length in attenuating the background acoustic field in the nozzle chamber might be considered to be caused by the establishment of a second standing wave pattern in the nozzle itself. For a nozzle of entrance length $l$, the frequency of the first and second harmonics will be given by $f_1 = \frac{c}{4l}$, $f_2 = \frac{3c}{4l}$. Table 1 shows the predicted and experimental frequencies for the two nozzle lengths used in the experiments. The
experimental values correspond to the strong pressure amplification regions in Figure 6.

**Table 1** First two harmonics of standing waves in the nozzles used in the experiments

<table>
<thead>
<tr>
<th>Nozzle Length</th>
<th>Model $f_1$ (kHz)</th>
<th>Model $f_2$ (kHz)</th>
<th>Experimental $f_1$ (kHz)</th>
<th>Experimental $f_2$ (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.95 cm</td>
<td>28</td>
<td>84</td>
<td>18</td>
<td>51</td>
</tr>
<tr>
<td>1.47 cm</td>
<td>18</td>
<td>54</td>
<td>13</td>
<td>39</td>
</tr>
</tbody>
</table>

Agreement with the model is poor, although the experimental results do indicate a ratio between the first two harmonics of $3:1$ as expected.

Another explanation of the attenuation and enhancement effect of the nozzle entrance length is based on a model for the admittance characteristics of the acoustic wave at the junction between the chamber and the nozzle entrance. Ignoring frictional attenuation, the effective admittance (volume flow/pressure excess) for a tube of length $L$ is given by [6]:

$$Y_{\text{eff}} = iY\tan\left(\frac{2\pi f l}{c}\right)$$

where $Y = \frac{A}{\rho c}$, $A =$ cross section of tube, $\rho =$ liquid density, $c =$ acoustic velocity in liquid.

The pressure wave is attenuated when

$$\left(\frac{2\pi f_n l}{c}\right)^n = \frac{(2n-1)\pi}{2}$$

or

$$f_n = \frac{(2n-1)c}{4l}$$

These are the same frequencies predicted for the establishment of standing waves in the nozzle entry length. However, under the admittance model, the predicted frequencies of Table 1 have the opposite effect to a standing wave. Pressure waves are strongly attenuated in the nozzle at these frequencies. This seems a more likely explanation to the experimental results of Figure 6.

**Summary and Conclusions**

The experiment results in this paper establish the transmission characteristics of pressure waves imposed on liquid jets emerging from drop generators of the type described herein. The pressure disturbance appearing at the orifice is highly sensitive to small changes in the liquid level in the reservoir and to small changes in the applied frequency. In the context of droplet production from the breakup of the liquid jet downstream of the nozzle, control of jet breakup length depends on maintaining constancy of the initial disturbance amplitude at the nozzle. This requires very tight control of both the applied frequency and the liquid level in the chamber.

The experimental results for the pressure amplitude variation in the reservoir chamber are well described by a simple one-dimensional model of an acoustic standing wave. However, the subsequent attenuation of the acoustic pressure wave transmitted through the nozzle still requires a fuller explanation. In particular, the experimental observation of significant enhancement of the acoustic pressure disturbance at the nozzle exit over certain narrow frequency bands can pose a problem for maintaining control on jet breakup length at frequencies close to these ranges.

**References**