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BRIEF COMMUNICATION

A NOTE ON THE EFFECT OF FORCED DISTURBANCES ON THE STABILITY OF THIN LIQUID SHEETS AND ON THE RESULTING DROP SIZE

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INTRODUCTION

A number of studies have been carried out into the stability of thin liquid sheets moving in a gaseous environment. Inviscid theories of two-dimensional wave growth predict that, in the initial stages of growth, an optimum frequency exists where the growth rate is a maximum. Viscous theory, on the other hand, predicts the absence of a wave of maximum growth rate except at low velocities. Some evidence of this has been provided by Crapper *et al.* (1975), who also suggest that dominant waves seen on a sheet must be of a frequency imposed by some external source. However, much of this data was subject to various sources of error since fan-shaped sheets of liquid were used. The sheets were viewed along their edges to record wave profiles but, since the waves tend to form along an arc centred on the orifice, distinct profiles could not be readily observed. Further, measurements had to be restricted to waves which had grown sufficiently to minimise masking by the sheet rims. The waves, therefore, might have grown in amplitude to a greater extent than that allowed by linear theory, and thus also have been affected by vortex growth in the surrounding air (Crapper *et al.* 1973). An additional error arose in calculating the growth rate since the initial wave amplitude was taken as being identical to the amplitude of vibration of nozzle. While two-dimensional sheets are approximated by fan-shaped sheets some distance from the nozzle where the rate of thinning is small, this is not the case within its vicinity. Here, the rapid rate of thinning can be expected to affect the initial rate of growth, and changes in amplitude must therefore be determined for waves growing beyond this region. The main purpose of the present work has been to develop a simple technique for obtaining growth rates of low amplitude waves at any distance from a nozzle orifice subjected to forced vibrations. Postulations that naturally occurring dominant waves are caused by perturbations produced from an external source have been investigated, and an account is given of attempts to isolate a nozzle from all external sources of disturbance.

EXPERIMENTAL

The technique used to investigate wave growth is to bring a needle gently towards the sheet until it just touches the succession of wave crests passing the particular location. A photograph is then taken of the needle point. The experiment is repeated at other axial positions on both sides of the sheet, all photographs being made on the same photographic plate. The resulting photograph consequently gives the locus of the wave crests from which growth rate can be determined. Water has been used for these experiments and fed to the nozzle by compressed air from a 2-litre pressure vessel. Details of the fan spray nozzles employed are given in table 1. The thickness parameter k represents the sheet thickness (h) at any distance (x) from the orifice, thus for nozzle X the sheet has a thickness of 11 μm, 10 mm from the orifice.

Table 1. Details of nozzles (G. Bray. Ltd.)

Manufacturer's designation	Orifice dimensions (mm)	k (=hx) mm^2
X	0.75 x 0.31	0.110
Y	0.46 x 0.27	0.055

RESULTS

Some results for a fan-spray nozzle subjected to forced vibrations normal to the plane of the sheet are shown in figure 1. The Ling 403 vibrator, employed for this work, could not produce a constant amplitude over the full range of frequencies employed and two values were used as shown. This is not considered to be of significance since growth rate should not depend on the size of the initial disturbance provided that it is not too large, and this is confirmed at frequencies where the two values overlap. The results demonstrate the absence of an optimum wave as suggested by Crapper. Further experiments have been carried out with a flat sheet produced by a 5 cm wide slit nozzle designed on the basis of that employed by Taylor (1959). The thinnest sheet that could be satisfactorily produced from the nozzle was 100 μm, and because of the limited amount of liquid available, the experiments were restricted to a velocity of 8.2 $ms.^{-1}$ As a result the two free edges rapidly converge to produce a relatively short sheet. Large initial amplitudes therefore had to be imposed in order that sufficient wave growth could occur for accurate observation. Because of the large mass of liquid in the nozzle the vibrator could only cope with those amplitudes up to a frequency of about 100 Hz. Figure 2 confirms the absence of an optimum frequency.

Examination of photographs of liquid sheets produced by fan spray nozzles which are subjected to forced vibrations (such as those published by Crapper 1975) show waves very similar in form to those which occur naturally. This supports the view that although the nozzles are ostensibly rigidly supported, the latter waves may be initiated by a low amplitude vibration of mechanical origin. An attempt was therefore made to detect these

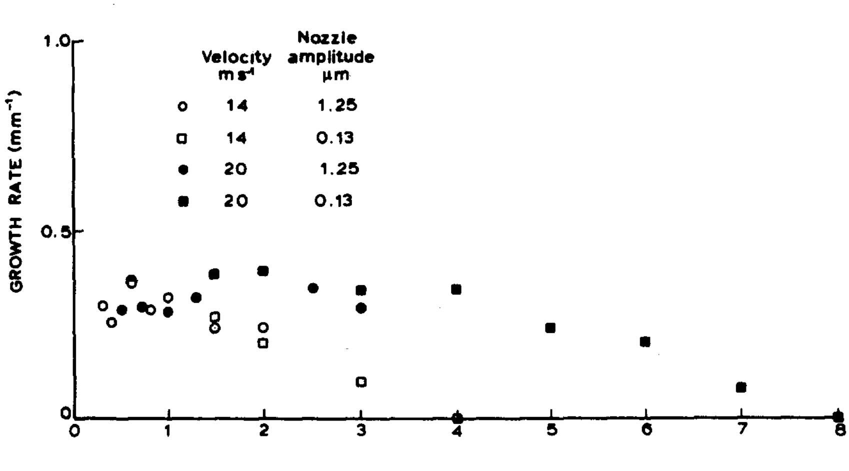

Figure 1. Variation of growth rate with frequency (Nozzle Y).

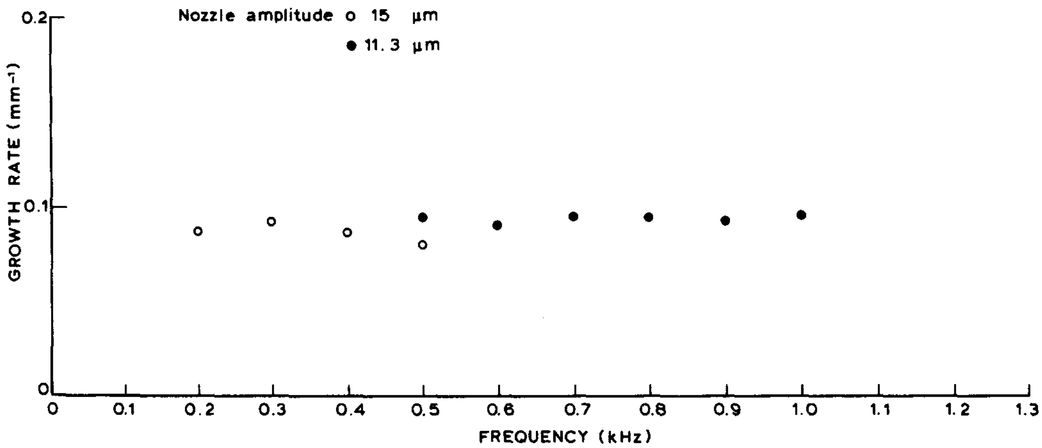

Figure 2. Variation of growth rate with frequency (Slit nozzle).

vibrations by means of a Piezo-electric accelerometer mounted on the nozzle with its output fed to a spectrum analyser. There was considerable electronic noise but a number of frequencies could be detected. Some results are plotted in figure 3 for a Bray "X" nozzle with sheet velocities of 19 and 30 ms^{-1}, corresponding to ejection pressures of 2.07 and 4.83 bar, respectively. The relative amplitudes of each frequency are represented by the heights of the vertical lines. The figure shows that the sheet velocity does not affect the vibration frequencies but affects the amplitude of vibration, the effect becoming more pronounced with increase in frequency. Corresponding dominant wave frequencies were measured from high speed cine films taken of the waves viewed along the edges of the sheets. The results are listed in table 2, together with the associated wavelengths and wave

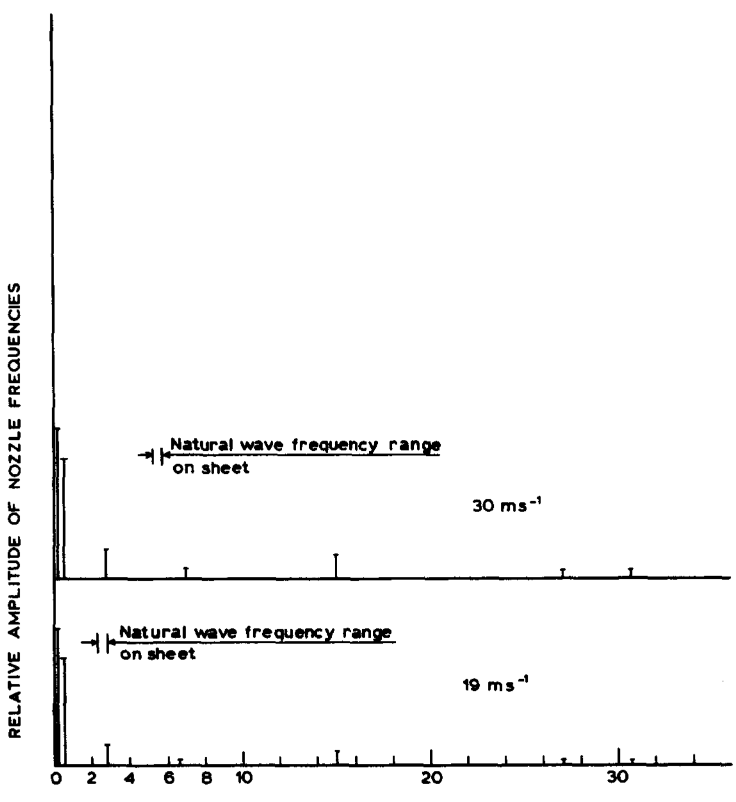

Figure 3. Nozzle frequency spectrum (Nozzle X).

Table 2. Wave characteristics

Sheet Velocity ms^{-1}	Measured wave frequency Hz	Wave velocity ms^{-1}
19.35 (2.07 bar)	2600 ± 200	13.3 ± 1
29.75 (4.83 bar)	5500 ± 200	21.5 ± 1

velocities. Sheet velocities given in the first column were measured by laser Doppler anemometry with equipment kindly loaned by DISA Ltd. Comparison of the wave frequencies with the nozzle frequency spectra shows that for the lower velocity sheet, wave frequency is close to the 2700 Hz line but for the other sheet, wave frequency lies between the 2700 and 6600 Hz lines.

An investigation was then carried out to determine the cause of the vibrations and it was found that the 2700 Hz line originated from resonance of the brass tube in which the nozzle was located, while vibrations of 500 Hz and less were due to disturbances arising from machinery in the building and resonance of the rig in which the apparatus was mounted. The cause of the higher frequencies could not be found, but their constancy with sheet velocity suggests that they are unlikely to be of hydrodynamic origin.

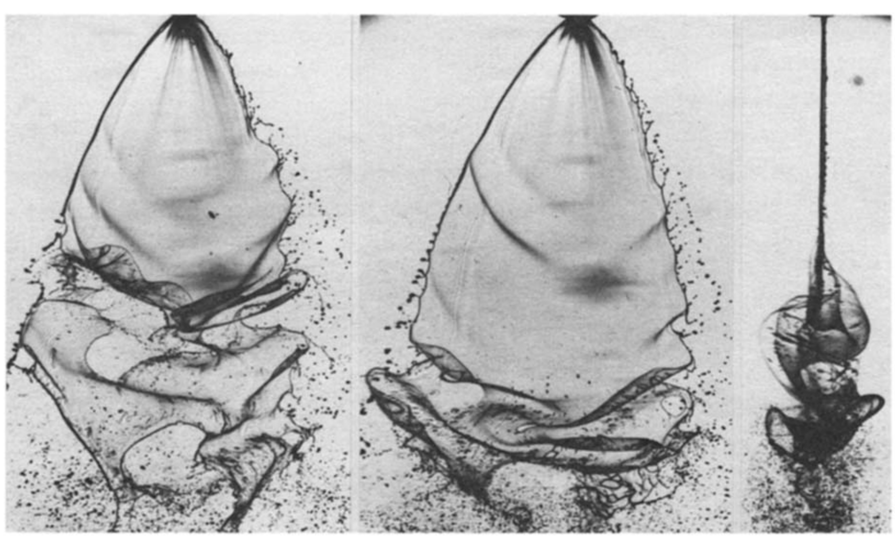

Figure 4(a). Characteristics of waves with "isolated" nozzle.

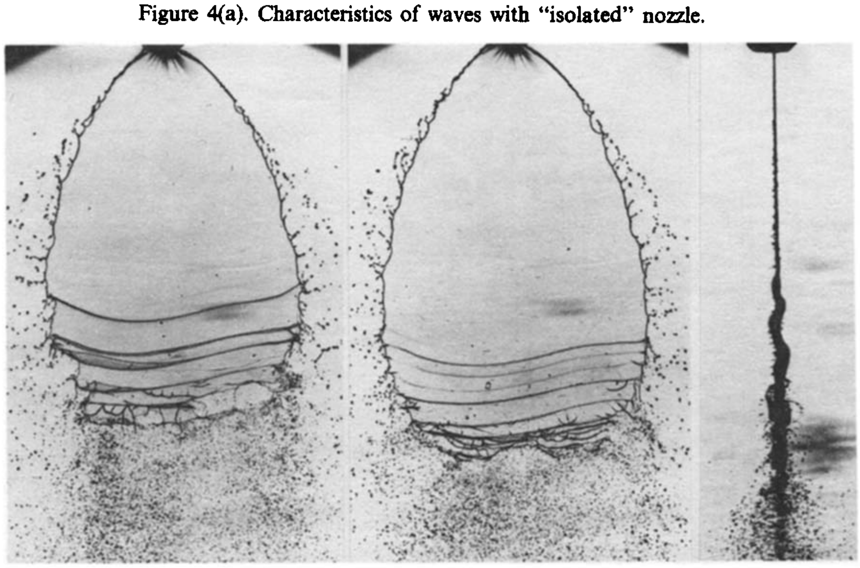

Figure 4(b). Characteristics of waves with conventionally held nozzle.

A further experiment was carried out to attempt to isolate the nozzle from all vibrations. The nozzle was soldered into a lead pipe which was supported on low frequency damping pads. Liquid was fed to the pipe via rubber tubing connected to the pressure vessel. No vibrations could be detected by the accelerometer, but the sheet exhibited a disturbed appearance, albeit different from its normal state. Figure 4(a) shows two typical photographs of the sheet taken at random instants, together with a single view along the edge. The photographs may be compared with corresponding ones in figure 4(b), which depict sheet break-down under normal conditions. The photographs reveal a change in the flow pattern, and, in conjunction with high speed cinephotography, a high amplitude low frequency (250 Hz) wave originating from the orifice. The frequency was independent of sheet velocity and subsequently found to correspond with the sideways movement of the rubber feed tube. The latter presumably provided axial pulsations to the liquid which were not detected by the accelerometer. The overall results are unexpected, and they reinforce the view that forced vibrations, either hydrodynamic or external often initiate the disturbances. We conclude that the dominant wave frequencies must result from the additive effect of the several frequencies imposed on the sheet, and the general finding, that they increase with sheet velocity, must result from the greater contribution of the higher frequencies under this condition.

In view of the finding that sheet breakdown is significantly affected by resonance of

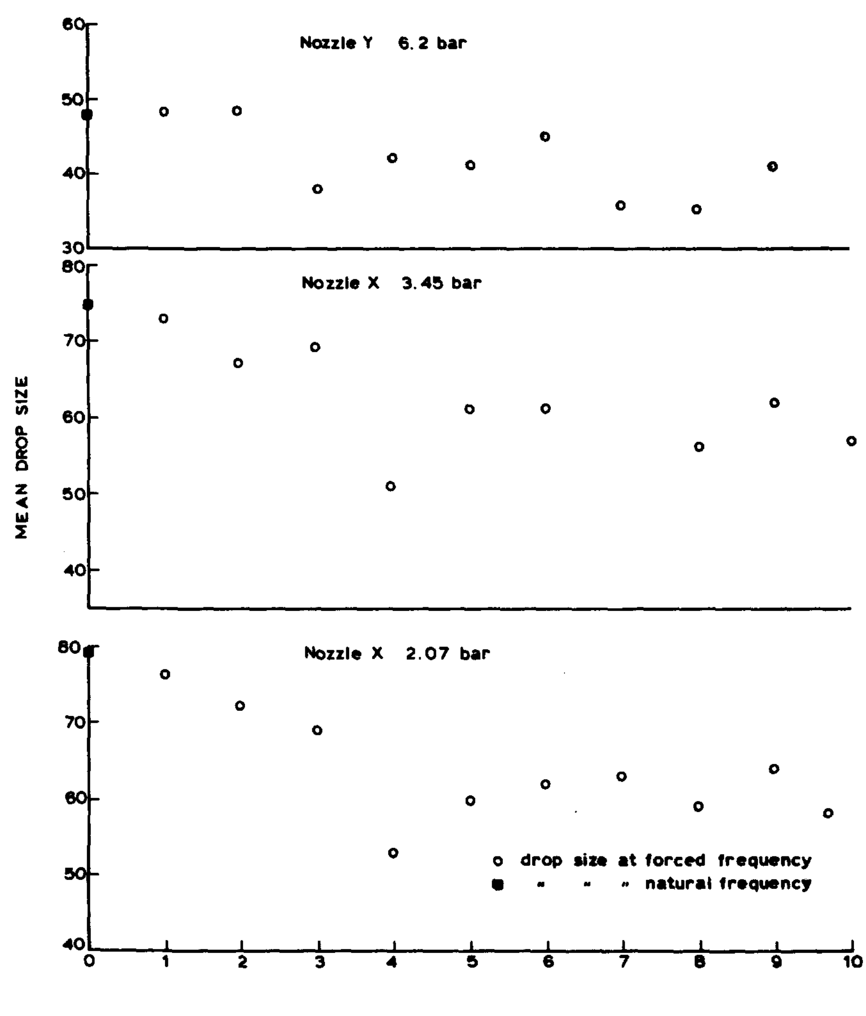

Figure 5. Variation of drop size with forced frequency.

the apparatus it is feasible that different experimental rigs may cause a spray nozzle to produce different drop-size spectra. In order to examine this hypothesis a few measurements were made of drop size for nozzles subjected to a range of transverse vibrations for a fixed amplitude of 0.25 μm. Some results expressed as vol/surface mean diameter ($\Sigma nD^3/\Sigma nD^2$) are presented in figure 5 for nozzles X and Y. In each case it is seen that drop-size tends to be constant with increase of frequency until a critical value is attained (4 kHz for nozzle X and 3 KHz for nozzle Y) when the drop size suddenly falls in value. For the nozzle X drop size subsequently increases and then remains effectively constant. For nozzle Y the results are too scattered to draw any firm conclusions, although there is a similar increase beyond the critical frequency. Drop sizes plotted at zero frequency correspond to atomisation in the absence of forced vibration. For nozzle X at 2.07 bar, the "natural" dominant frequency is 2600 Hz, but the drop size should not be compared directly with the corresponding forced value, since the "natural" nozzle amplitude was estimated to be much smaller than the "forced" value.

The results suggest that drop size may be affected by both nozzle amplitude and frequency. Since these factors may depend on natural frequencies in the apparatus, drop sizes in industrial applications could well turn out to be different from those given by the same nozzle in a laboratory test. The industrial user should be warned that the drop size is likely to be a property of the location as well as of the nozzle.

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