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ON TRANSIT TIME INSTABILITY IN LIQUID JETS

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16. Abstract
The purpose of the study is to find a basic transit time instability in flows with disturbances of speed. It was shown that the mass distribution is established by and large by the described transit time effects. These transit time effects may also be involved for gas jets.

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ON TRANSIT TIME INSTABILITY IN LIQUID JETS

G. Grabitz and G. Meier

Important aspects of the disintegration of liquid jets can be explained simply by transit time effects. But such phenomena certainly play a role in all velocity modulated flows. To discuss this situation we will first indicate here an exact solution of the differential equations of flow. By comparing this theoretical result with our own water jet experiments we will then show that a relationship can be produced with the stability of the jet. /1*

Theory of the Monodimensional Liquid Jet

We are considering here the liquid jet in the field of gravity (earth's acceleration g) of a friction free, monodimensional, unstationary problem without surface tension. The pressure in the jet is superimposed by the external pressure. Thus the velocity components u(x,t), v(x,t) and the cross-section area F(x,t) are the flow quantities determining the jet (compare Figure 1). The time is designated as t, the x-coordinate is in the direction of the speed of outflow uA(t) from the nozzle. The angle gives the slope of the x-axis against the horizontal. The equations of conservation of mass and momentum are

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -g \sin\gamma$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} = -g \cos\gamma$$

$$\frac{\partial F}{\partial t} + u\frac{\partial F}{\partial x} + F\frac{\partial u}{\partial x} = 0$$

with the pregiven values for x=0; u=uA(t), v=0 and F=FA. /2

*Numbers in the margin indicate pagination in foreign text.

By introducing the Lagrange coordinates according to

$$t(\vartheta,\tau) = \vartheta \ ,$$
$$x(\vartheta,\tau) = u_A(\tau)\,(\vartheta-\tau) - \frac{g \sin\gamma}{2}(\vartheta-\tau)^2$$

our basic equations are greatly simplified:

$$\frac{\partial u}{\partial \vartheta} = -g \sin\gamma \ ,$$
$$\frac{\partial v}{\partial \vartheta} = -g \cos\gamma \ ,$$
$$\frac{\partial F}{\partial \vartheta} = F\,\frac{\frac{du_A}{d\tau} + g \sin\gamma}{u - \frac{du_A}{d\tau}(\vartheta-\tau)} \ .$$

The pregiven values are now $\vartheta = \tau$: u=uA(τ), v=0, F=FA.

We derive them easily in the form of an exact solution the flow quantities as a function of the actual time ϑ and the time τ at which the flow particles leave the nozzle with the initial velocity uA(τ):

$$u(\vartheta,\tau) = u_A(\tau) - g \sin\gamma\,(\vartheta-\tau) \ ,$$
$$v(\vartheta,\tau) = -\,g \cos\gamma\,(\vartheta-\tau) \ ,$$
$$F(\vartheta,\tau) = \left| \frac{F_A\,u_A(\tau)}{u_A(\tau) - \left[g \sin\gamma + \frac{du_A}{d\tau}\right](\vartheta-\tau)} \right| \ .$$

As examp : we choose here for the time dependence of the speed on the nozzle a sinusoidal disturbance superimposed on the constant basic velocity $\bar{u}$: /3

$$u_A(\tau) = \bar{u}(1 + \varepsilon \sin(\omega\tau))$$

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and introduce the nondimensional time $\hat{\tau} = \tau \bar{u}/RA$ ($RA=\sqrt{FA/\pi}$). In our solution

$$\frac{F}{F_A} = \frac{1 + \varepsilon \sin(\Omega \hat{\tau})}{\left| 1 + \varepsilon \sin(\Omega \hat{\tau}) + [G - \varepsilon \Omega \cos(\Omega \hat{\tau})] (\hat{\vartheta} - \hat{\tau}) \right|}$$

three nondimensional parameters occur with the interference of velocity ε, the Froude number $G=gRA \sin\gamma/\bar{u}^2$ and the Strouahal number $\Omega=\omega$ by $RA/\bar{u}$. If the disturbance $\varepsilon > G/\Omega$ then the solution has points of infinity. From the point x=0 (that is $\hat{\vartheta} = \hat{\tau}$) before the first infinity point at periodical distances with the running length increasing maxima of the jet cross-section arise. After the first infinity point the x-axis is covered in a multiple way by flow material. Before we can achieve by comparison with the experiments the physical explanation of this situation, it may be established here that the mass collection in the jet in accordance with the hypotheses of our theory can arise only by collection or overtaking processes of the liquid particles of the jet, since interactions of the particles with each other are not taken into consideration.

For $\varepsilon < G/\Omega$ the disturbances of the jet are damped. In quantities with dimensions, the corresponding conditions for the speed disturbance is $\delta u < g/\omega$.

Experiments with Water Jet and Comparison with Theory /4

A schematic representation of the experimental plant is given in Figure 2. The tube which can swivel around the longitudinal axis (internal diameter 25 mm) of the jet equipment has an inlet from a pump through a throttle resistance and an outlet through a nozzle (internal diameter 3 mm). The flow can be perturbed by a piston at the end of the tube with a pregiven frequency. The measurement of the perturbing amplitude takes place through a pressure convertor which is also applied laterally on the tube. Figure 3 shows a flashlight photo of a jet flowing out horizontally. Below it gives the corrected variation for the same frequency (Strouhal number 0.15) and the same disturbance (= 5.5 %) for approximately the same phase position of the disturbance. The low curve represents the cross-section area. This curve is partly doubly covered. The peaks correspond each time to the reversal edges of the undulating course of the jet shown above. In the experiment the exchange of momentum and surface tension in an early study caused the formation of the drop which lies in the doubly covered region between the two peaks of the mass collections and continues as a rigid body (held together by the surface tension). The residual flow material which was not connected in the drop is arranged in accordance with the theoretical curve.

Figure 4 shows a comparison of theory and experiment for the jet directed upwards in a vertical direction. The jet is somewhat inclined in the experiment in order that the material falling back flows away laterally. The disturbance increases in a very similar way in the theory and experiment. Whereas according to our simple theory a double covering occurs, in the experiment there is a tearing away of the jet. Here the surface tension is certainly involved, but this tearing can be under- /5
stood even with the change of momentum. In the region of the double covering an average speed arises and therefore a discontinuity of speed with regard to the neighboring particles in which there is no double covering. A forwards jump in speed means practically the breaking away of the jet.

Figure 5 shows the comparison of the theory and experiment for the jet directed vertically downwards (water cock). The Strouhal number is 0.54 and the disturbance is speed is here 1.1 %. This picture may be used as illustration of our stability findings for the jet directed vertically downwards: here too the smallest perturbation is excited if only the perturbing frequency is high enough.

Summary

The purpose of this study is to discover a basic transit time instability in flows with disturbances of speed. The impression should not be

aroused that the surface tension or the Helmholtz instability is not important for the disintegration of the jet. Precisely for liquid jets the surface tension is important for constriction and drop formation as well as in particular to explain the production of very small drops, the so-called satellites. But we believe that we have shown that the mass distribution is established by and large by the transit time effects described. Therefore even in the case of gas jets once should in the individual case consider whether in the disintegration of the jet there is really pure shear layer instability, or whether a transit time instability produced by velocity fluctuations in the jet is the cause of /6
vortex formation. If up to now the described effect has not been duly considered, this seems to be why the ordinary descriptions of the disturbances excited by means of harmonic functions can represent only with difficulty the nonlinear process of the waves caused by transit time effects and varying constantly in x and t.

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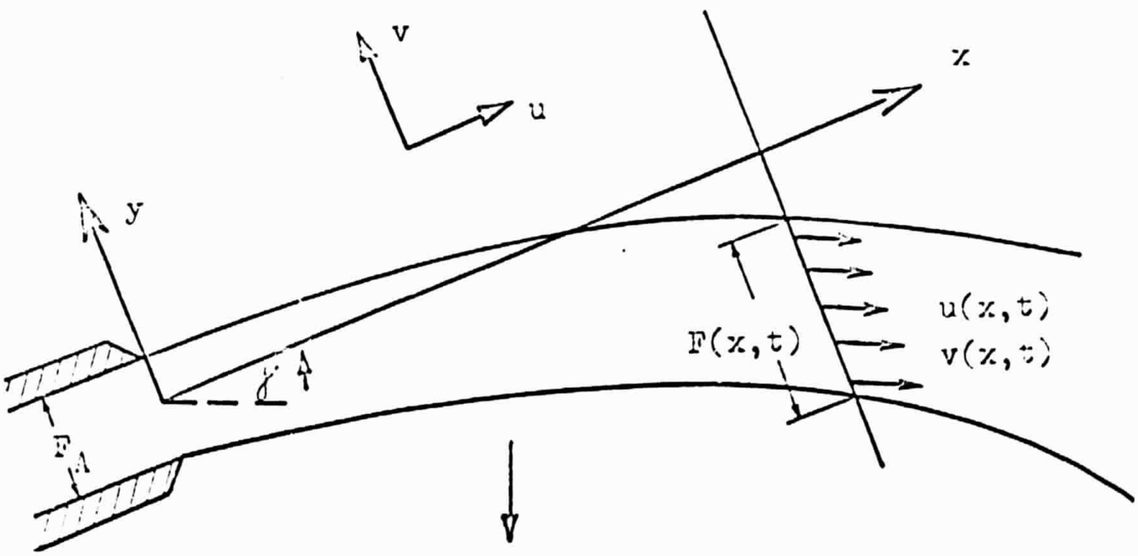

Figure 1: Notations

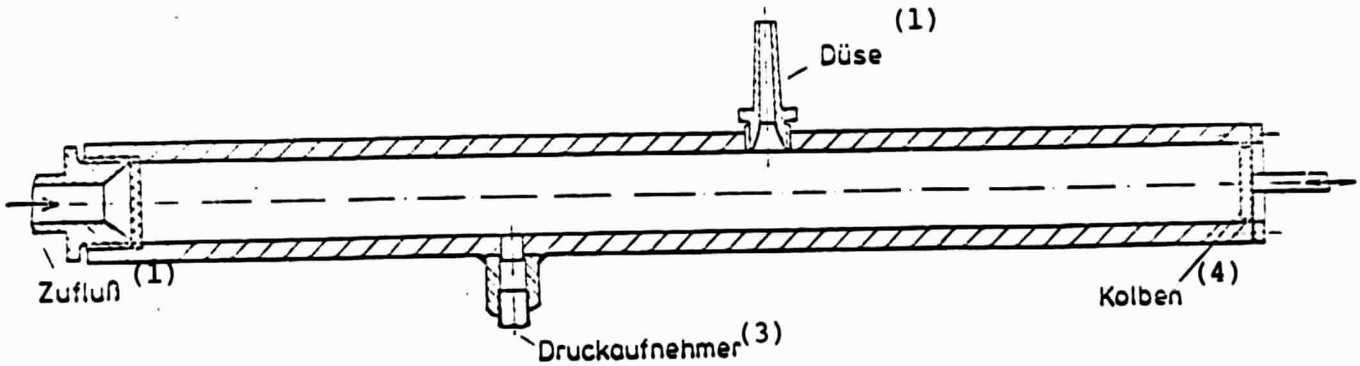

Figure 2: Schematic representation of the experimental plant.
Key: (1) inlet; (2) nozzle;
(3) pressure transducer;
(4) piston.

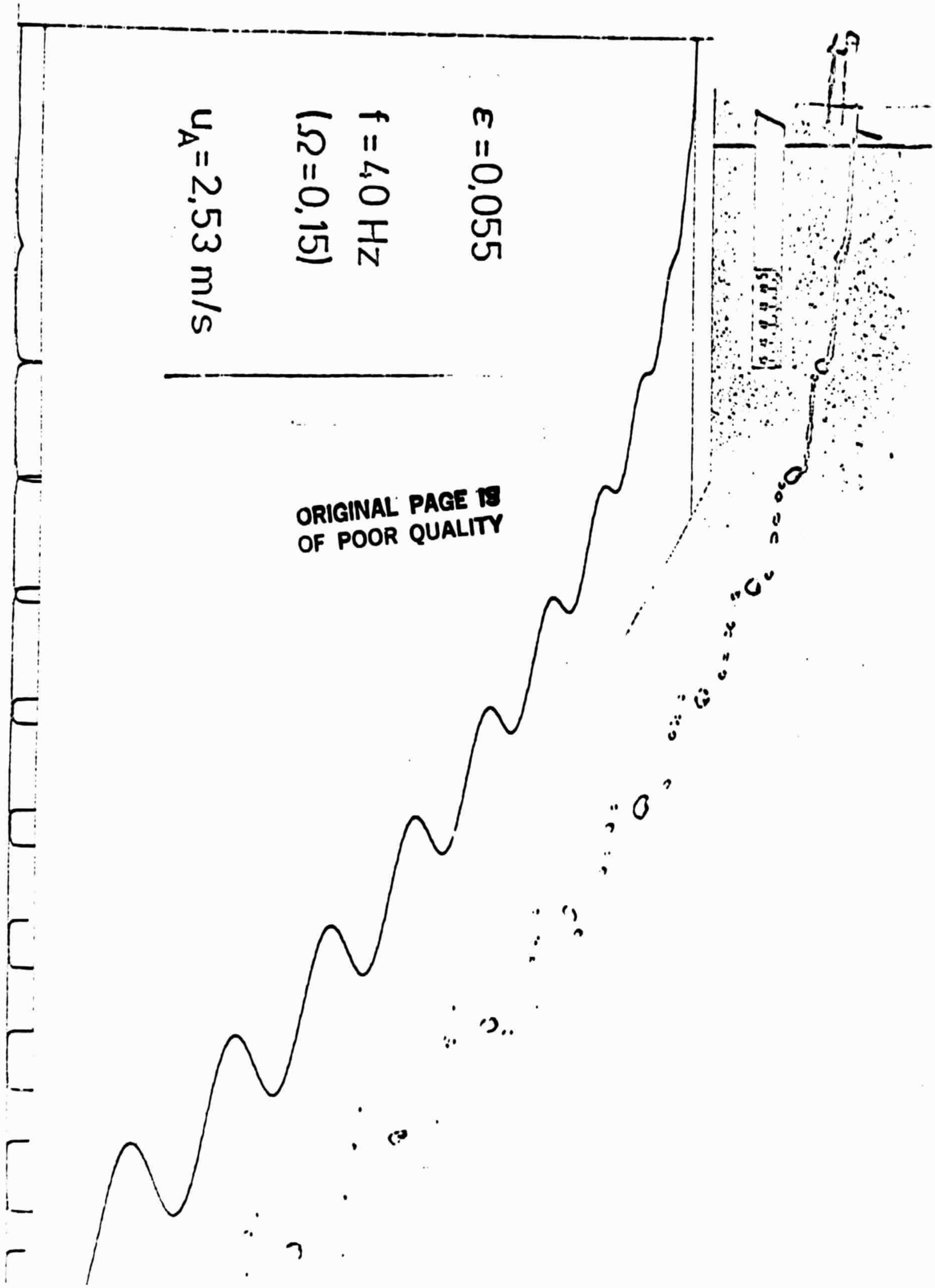

Figure 3: Water jet flowing out horizontally with perturbed initial speed (frequency 40 hz, amplitude 5.5 percent). Top: flashlight photo; Center: calculated variation; Bottom: cross-section of the beam.

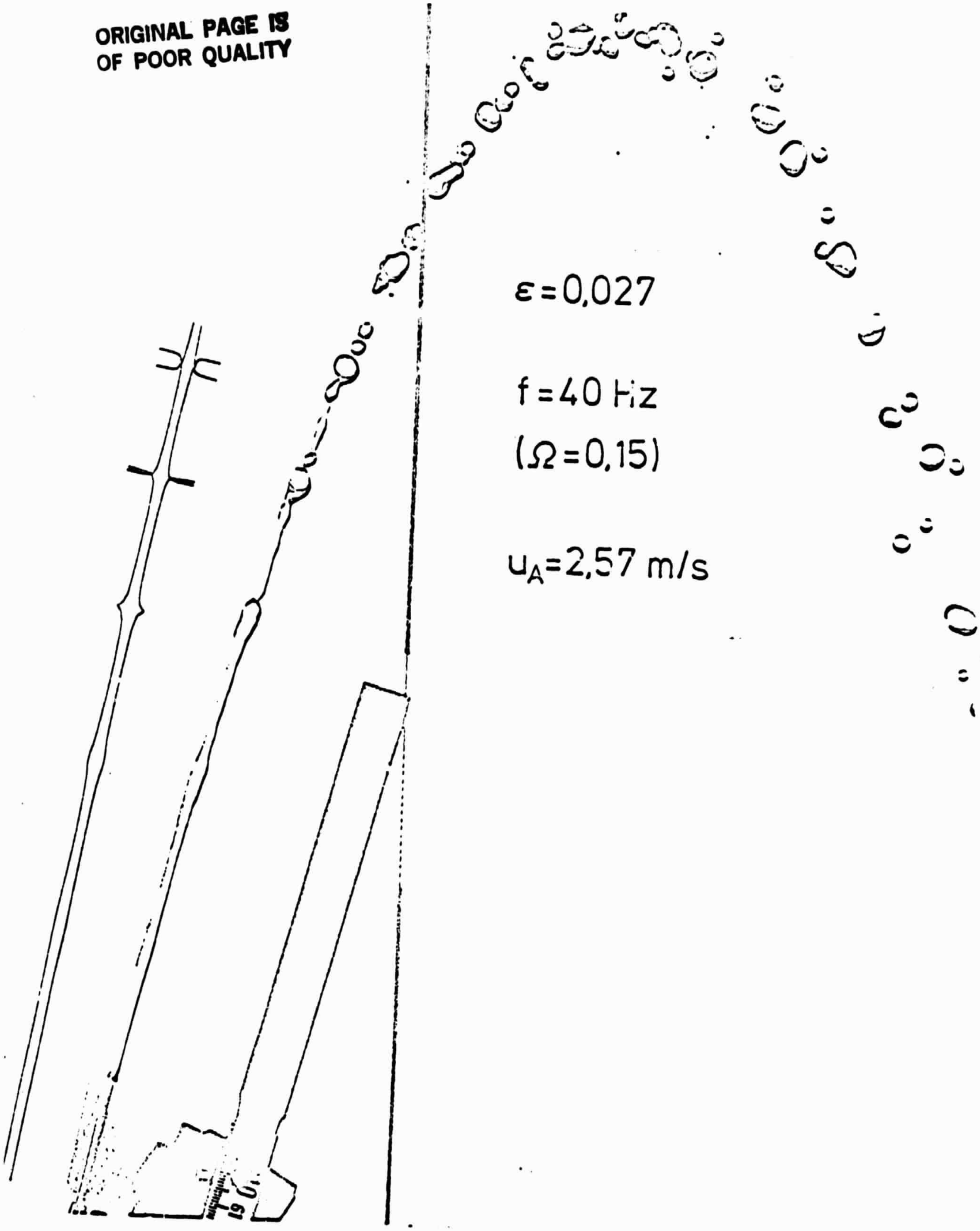

Figure 4: Water jet flowing out upwards with disturbed initial velocity (frequency 40 Hz, amplitude 2.7 percent). Flashlight photo and calculated jet (with rotation symmetry).

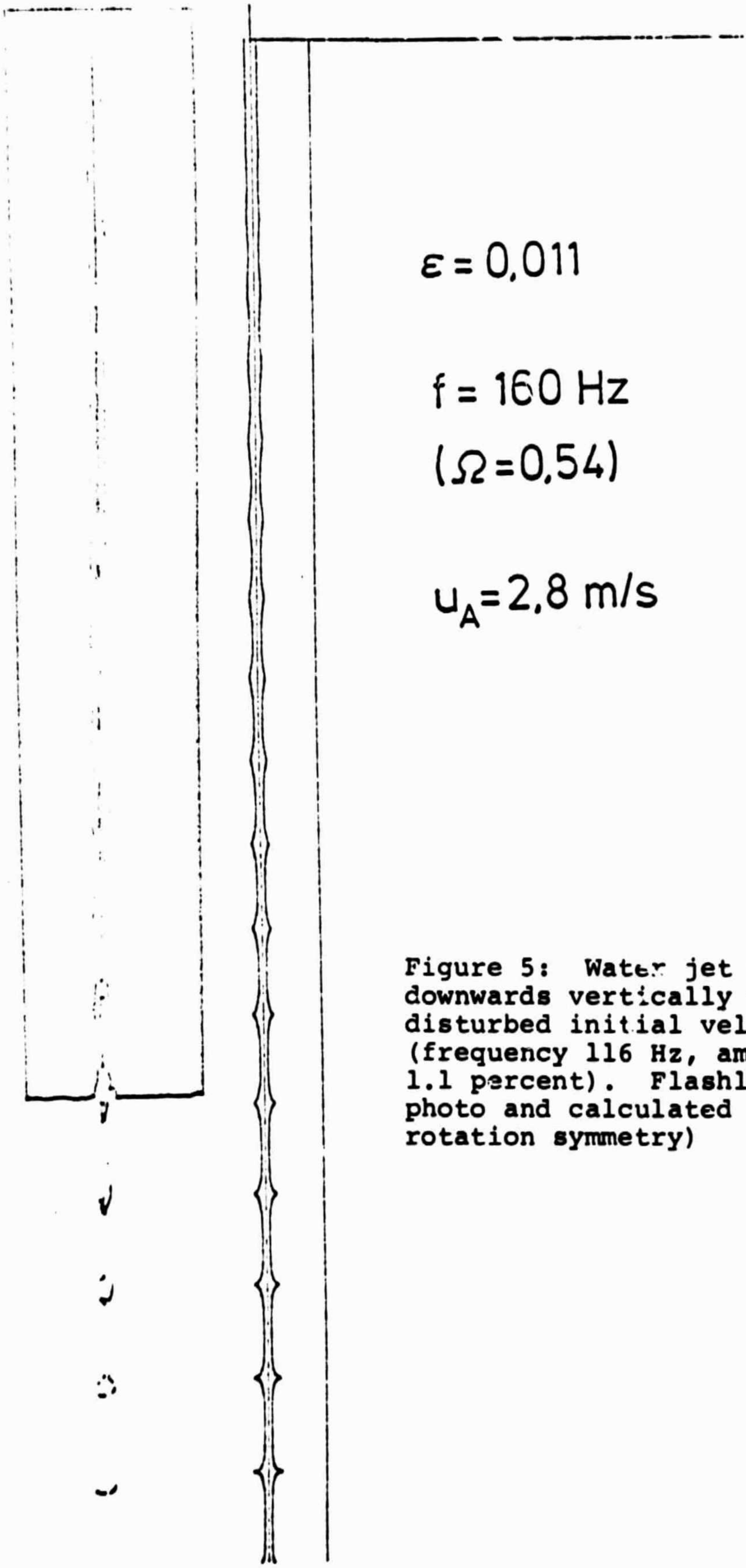

Figure 5: Water jet flowing downwards vertically with disturbed initial velocity (frequency 116 Hz, amplitude 1.1 percent). Flashlight photo and calculated jet (with rotation symmetry)