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ENTRAINMENT CHARACTERISTICS OF
UNSTEADY SUBSONIC JETS

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INTRODUCTION

The entrainment mechanism in turbulent jets has been a subject of considerable basic and applied interest for many years. Recently, this problem has received increased attention because of the need to develop compact, yet highly efficient thrust augmenting ejectors for VSTOL applications¹. Several new techniques have been introduced or proposed to increase the jet entrainment e.g., hypermixing², swirling³, acoustic interaction⁴ and unsteady jet techniques⁵. It is the objective of this paper to present recent results on the entrainment characteristics of two types of unsteady jet flows, i.e., oscillating jets with time-varying jet deflection and pulsating jets with time-varying mass flow.

The use of oscillating jets for enhanced flow entrainment was first advocated by Viets⁵ who also developed a rather ingenious fluidic jet actuation device. Other oscillating jet studies have been reported^{6,7,8,9} but they do not contain entrainment measurements.

The favourable effect of pulsating jets on flow entrainment seems to have been first recognized during the development of the pulse jet engine^{10,11,12}. Lockwood¹⁰ also noted the generation of ring vortices due to pulsating flow, an effect later verified more clearly by Curtet and Girard¹³. Further pulsating jet studies are those of Johnson and Yang¹⁴, Didelle et al.,^{15,16} Binder and Favre-Marinet¹⁷, Crow and Champagne¹⁸ and, very recently Bremhorst and Harch¹⁹.

The following section is a report of three different experiments which were conducted to assess the effectiveness of jet unsteadiness in enhancing flow entrainment.

EXPERIMENTS

Definition of the edge of a turbulent jet raises subtleties which are discussed by Crow and Champagne¹⁸ in terms of the turbulent (or inner rotational) region and the induced potential flow (or potential tails). In the experiments mean volumetric flow rates $Q(x)$ in the turbulent region of unsteady subsonic jets were determined at a number of distances x from the nozzle by integration of mean jet velocity distributions. A constant temperature hot-wire anemometer was used in all cases and the mean of its linearized output was assumed to be proportional to the mean velocity in the direction of the center line of the nozzle. Errors arising from estimation of the edge of the turbulent region and from the influence of high ratios of rms to mean velocities near the edge of the jet are regarded as tolerable in this investigation.

Various measures of entrainment are defined in the literature. Here, entrainment is defined as $(Q(x) - Q_R)/Q_R$ where Q_R is a reference flow rate and is properly taken as the mean volumetric flow rate Q_E at the nozzle exit in two of the experiments. In the third experiment Q_R is taken, for lack of precise nozzle flow rate information, as the volumetric flow rate Q_1 at a station near the nozzle in a steady jet. This still enables comparisons and is discussed later in more detail. Clearly, the entrainment differs by unity from the dimensionless local flow rates $Q(x)/Q_R$ which are presented in this paper.

Fluidically Oscillated Three-Dimensional Jet

The fluidic nozzle illustrated in figure 1 was used by the first and second authors to exhaust a jet of air with oscillating angle into still air.

The nozzle was based on a design by Viets⁵. Flow from a plenum chamber and a contraction emerges from a 6.2 x 49.0 mm rectangular section into a rapid diffusion section where it is bistable because of the proximity of the walls. The flow is illustrated at the moment it attaches to the lower wall A. This sets up an entrainment process and generates compression and rarefaction waves in the feedback tube connecting control parts A' and B'. Continuous jet oscillation results at a frequency which depends on the length of the feedback tube.

In both the oscillating and the steady tests the nozzle was operated at a pressure ratio of 1.13 to produce a mean mass flow rate of 0.0188 kg/s as measured with an upstream orifice plate. The jet oscillated through about 7 degrees either side of the nozzle center line and with a fundamental frequency of 52 Hz. However, higher harmonics were appreciable because of the flip-flop mode of operation. Viets⁵ showed that velocity fluctuations at the half-width position of the mean velocity profile have almost a square wave shape.

The values of volumetric flow rate $Q(x)$ used in figure 2 were obtained by integration of the mean velocity distribution across the jet cross-sections. The limits of integration were stations at which the mean velocity was between 5 and 10 percent of the maximum value in a distribution. This necessitated mild extrapolation of the distribution furthest downstream so that the value of $Q(x)$ there has a possible error of about 10 percent.

For the two cases of oscillating and fixed jet angle, $Q(x)$ is normalized by the mean volumetric flow rate Q_E at the nozzle exit. Mass flow rate upstream of the nozzle (measured with an orifice plate) was used to determine Q_E . The hydraulic diameter of the nozzle ($4 \times \text{area}/\text{perimeter}$) is used as the length scale because of the essentially three-dimensional

nature of the flow. The change in slope of the curve of $Q(x)/Q_E$ for the steady jet is attributed to the transition from a high aspect ratio three-dimensional flow to a more axisymmetric mean flow.

Mechanically Oscillated Two-Dimensional Jet

Recent two-dimensional studies of flow past an airfoil at zero incidence and with an oscillating trailing edge jet flap have been extended by the first and second authors to measurements of entrainment. Details of the mechanically oscillated nozzle have been reported previously^{9,20}. In these tests the nozzle was oscillated through 5.2 degrees either side of the airfoil chordline and at frequencies of 4 and 20 Hz. The free stream velocity was 29.2 m/s and the nozzle exit velocity of 137 m/s was estimated, using the results of Bradbury and Riley²¹, from measurements of the velocity profile close to the nozzle with the jet held parallel to the free-stream.

The instantaneous velocity profiles measured in a previous study²⁰ were averaged over a cycle of nozzle oscillation to obtain mean velocity profiles and hence mean volumetric flow rates. Because nozzle velocity was not measured directly the measurements in figure 3 for the oscillating and the steady cases are both normalized by the volumetric flow rate in the steady jet across the measuring section nearest the nozzle (i.e. 35 nozzle widths downstream). The use of a small nozzle width (0.38 mm) and measuring stations many nozzle widths downstream is a legacy of the preceding studies of jet flaps and leads to an uncertainty in $Q(x)/Q_1$ which increases to about 10 percent at the downstream limit. Nevertheless, the measured insensitivity of $Q(x)/Q_1$ over the range of x to the frequency of oscillation is significant. It must be stressed that the jet flowed into a moving air-stream.

Axisymmetric Jet with Pulsed Core

Bremhorst and Harch¹⁹ recently studied a fully pulsed axisymmetric air jet exhausting into still air and their measurements of $Q(x)/Q_E$ are reproduced in figure 2. They used a mechanical valve connected to a plenum chamber by a smooth transition piece. The valve allowed flow for one third of its period of cyclic operation. The first and third authors used the same valve to study an axisymmetric air jet flowing into still air but with pulsation restricted to the inner core by the fitting of a two-stream coaxial nozzle downstream of the valve (figure 1). The nozzle consisted of a central reducer with 6.9 mm exit diameter to which air was supplied solely from the pulsating valve, and an annular section of 25.4 mm diameter which was fed through a regulating valve with air taken from upstream of the plenum chamber.

The total jet flow rate was measured with a flow meter well upstream of the plenum chamber. The inner coaxial jet flow rate for the pulsed core was metered separately upstream of the plenum chamber. The mean exit velocities for the steady annular portion of the jet and the pulsed core were 18.3 and 12.6 m/s respectively.

The results in figure 2 were obtained by planimeter integration of the radius times local mean velocity versus radius profiles. These profiles were faired to zero in order to exclude the potential tails as was done by Crow and Champagne¹⁸. The total volumetric flow rate across a downstream section was then normalized by the mean volumetric flow rate at the nozzle exit. Measurements by Crow and Champagne¹⁸ for a steady axisymmetric jet are presented for comparison.

DISCUSSION

The results in figure 2 show the powerful effect of full jet pulsation on entrainment. Also, the entrainment is seen to increase with frequency, but measurements are available for only two frequencies. Pulsation of only the jet core still provides significant entrainment benefits over the steady jet (figure 2) and this method can be regarded as an entrainment control device which enables the setting of the desired entrainment level for a jet of given flow rate. The fluidically oscillated jet shows equally significant entrainment increases (up to 55 percent increase in $Q(x)/Q_E$ at the most downstream station) when compared in figure 2 with the steady jet. Similar results with the same fluidic nozzle operated at a higher pressure ratio (1.33) were obtained by Veltman²² with a cruder measuring technique (pitot-static tube). Finally, in figure 3 the volumetric flow rate measurements for the sinusoidally oscillated jet flap show negligible variation from the corresponding steady jet measurements. This indicates that any significant influence of jet oscillation on the entrainment processes must, if it exists, be confined to the as yet uninvestigated vicinity of the nozzle.

These results indicate that entrainment depends on the type and amount of jet unsteadiness. Apparently the mere introduction of jet unsteadiness by small sinusoidal flow angle variations is insufficient to enhance entrainment but it should be noted that the results in figure 3 were obtained at measuring stations which are all many nozzle widths downstream of the jet nozzle. Thus, no fully conclusive statement can be made at this time about the entrainment close to the nozzle. However, the measuring stations for the sinusoidally oscillated jet were all within less than one half of

the jet wave length. Therefore, the sinusoidally oscillated jet was operated at a much smaller reduced frequency than the other two jets. In effect, it approached quasi-steady conditions which may well explain its low entrainment. Indeed, in two previous papers^{20,23} it was shown that quasi-steady concepts are quite successful in explaining the major flow features.

The high entrainment of the fluidically oscillated jet would appear to be caused by the high-frequency content of this square wave type of oscillation but more detailed measurements are clearly needed, in particular for the fluidically oscillated and the pulsed jets. Such studies are presently in progress. Furthermore, practical ejector application requires the proper trade-off between entrainment and primary nozzle thrust efficiency. While some information is available on the thrust efficiency^{5,22} of the fluidic nozzle there seems to be none available for pulsating nozzles.

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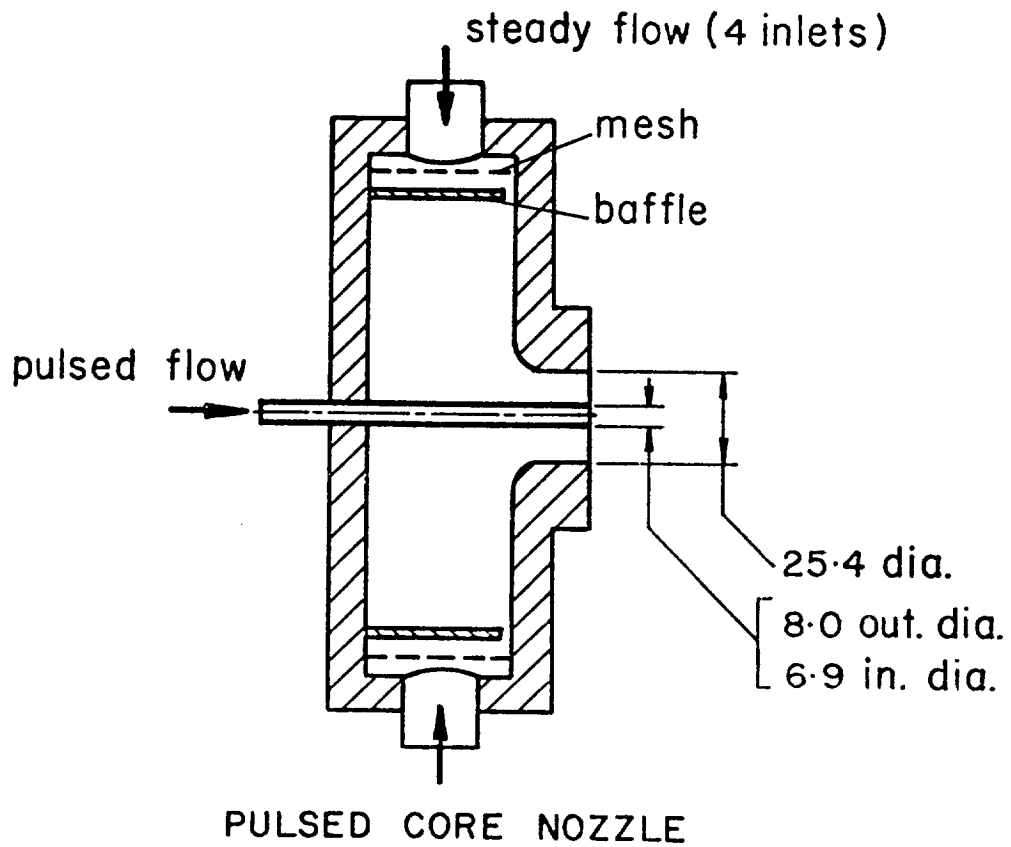
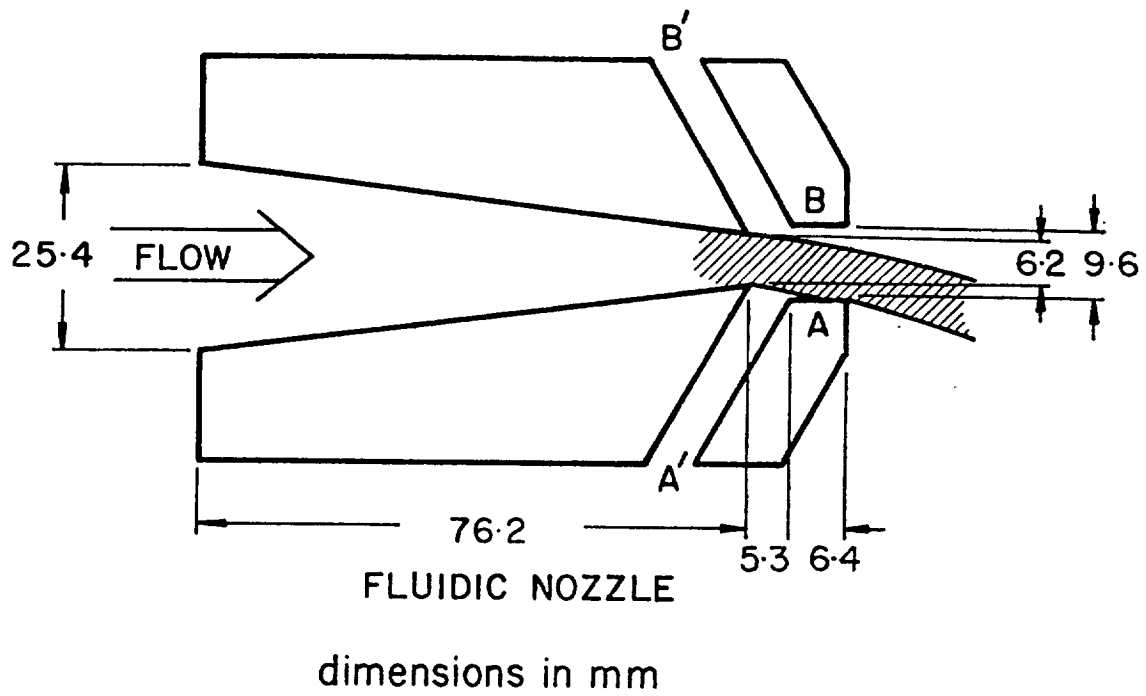


Figure 1. Schematic of fluidic and pulsed core nozzles.

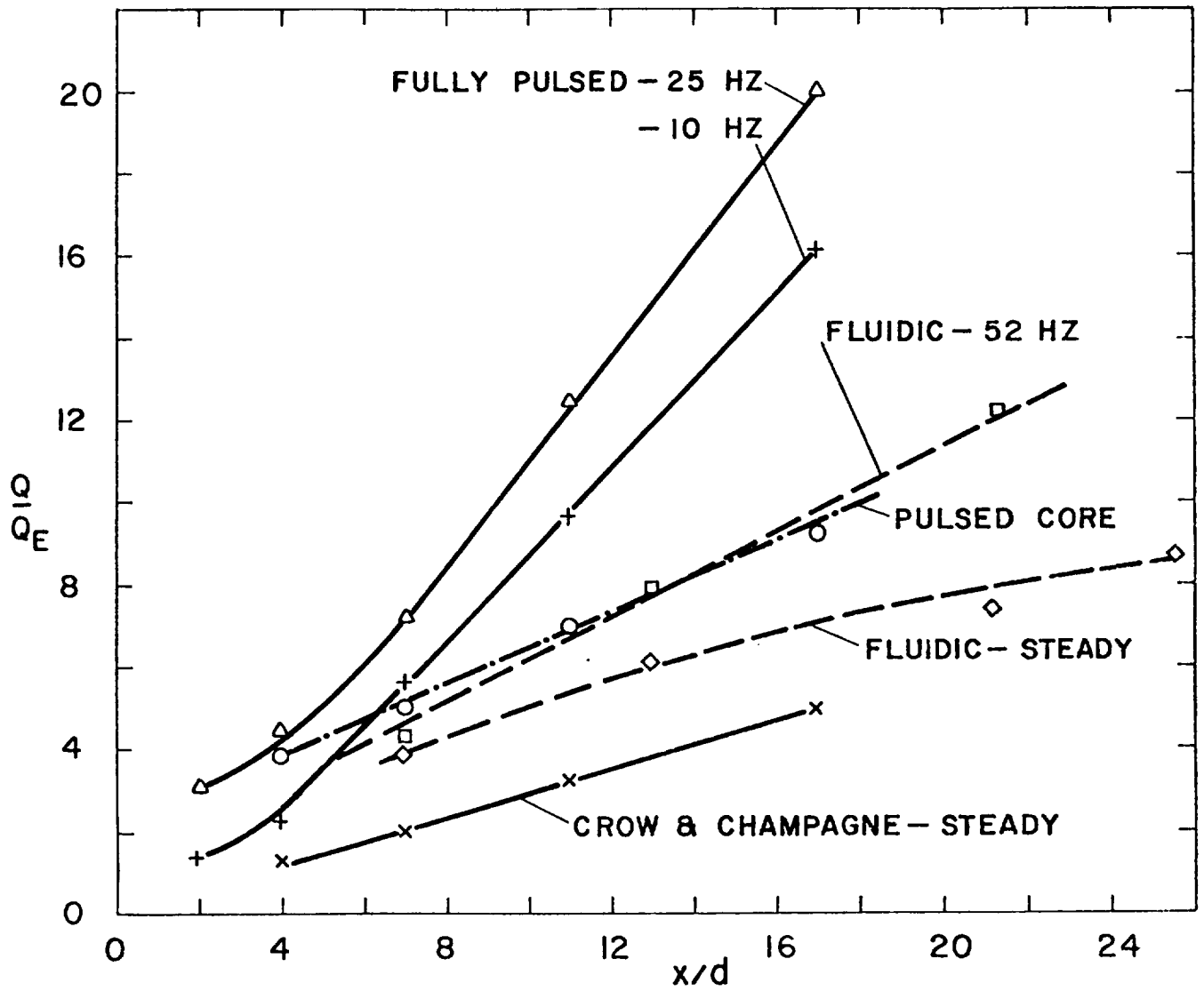


Figure 2. Mean volumetric flow rates $Q(x)$ versus streamwise distance x for fluidic, fully pulsed and pulsed core nozzles. Q_E is mean nozzle exit flow. d is hydraulic diameter of fluidic nozzle or diameter of axisymmetric nozzles.

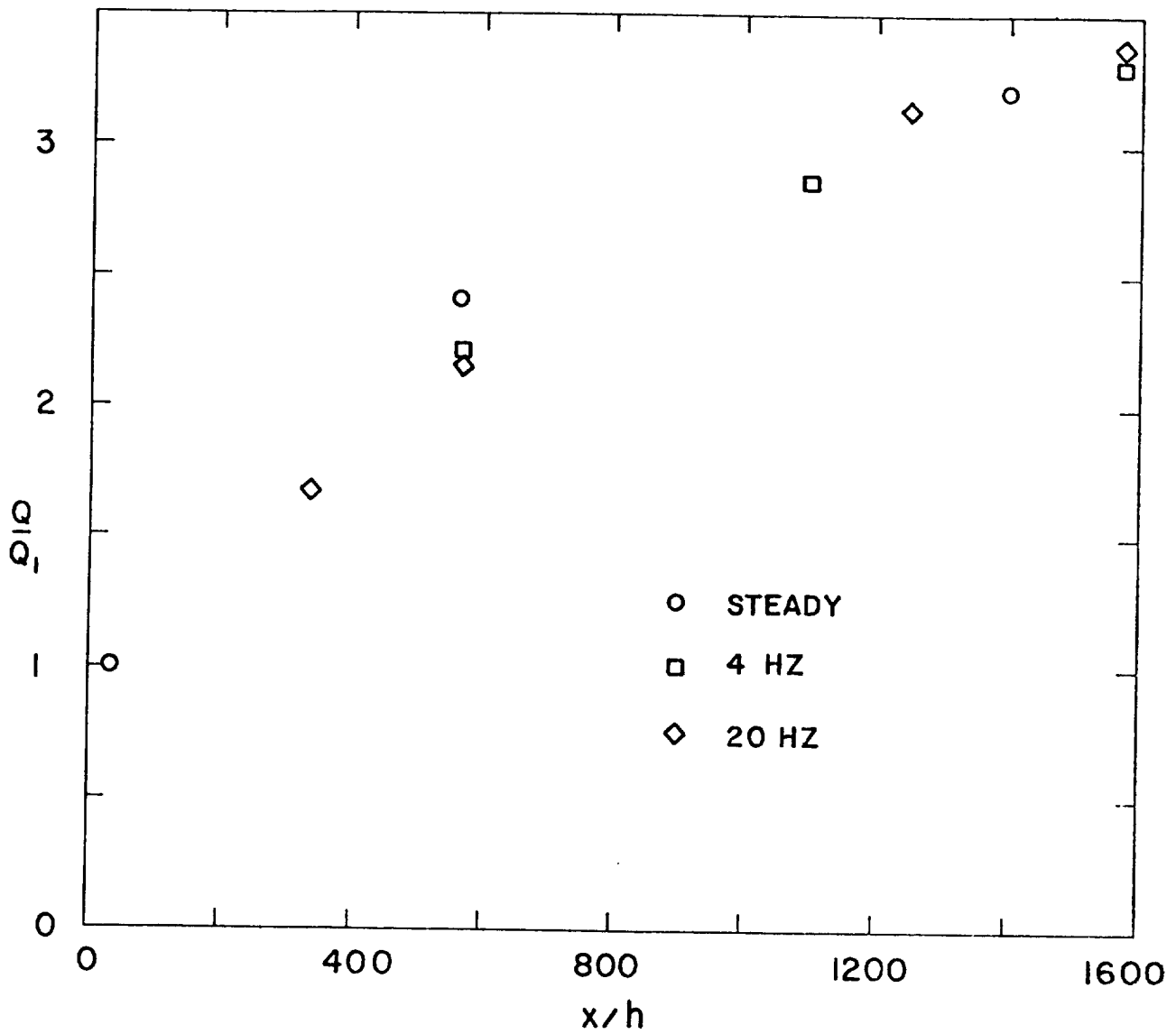


Figure 3. Mean volumetric flow rates $Q(x)$ versus streamwise distance x for mechanically oscillated two-dimensional jet. Q_1 is flow in steady jet at $x/h = 35$. h is nozzle width.