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# Two-dimensional jet subjected to periodic oscillations in the potential core region

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## Abstract

A two-dimensional subsonic jet was subjected to small periodic oscillations in its potential core region by vibrating a thin symmetric airfoil. Significant increase in the width of the jet and entrainment was observed due to excitation. The effect of the amplitude as well as the frequency of vibration on the jet was investigated. The mean velocity profiles of the excited jet exhibited similarity.

Key words : Jet, turbulence, fluid mechanics, unsteady flow.

## 1. Introduction

The behaviour of a jet subjected to forced excitation has drawn considerable attention in recent years[1-8]. It is observed that even small amplitudes of oscillation imposed on the jet produce a large spread of the jet with appreciable increase in entrainment. A subsonic jet could be excited by several means, namely, acoustic excitation, mechanical vibrations and fluidic devices[6]. The rapid spread of the jet due to excitation is the result of the increase in mixing between the flow issuing from the nozzle and the ambient fluid surrounding it.

Recently Simmons *et al*[4] observed that the excitation of a two-dimensional jet by an oscillating vane placed downstream of the nozzle exit in the potential core region has an advantage over an internally pulsed jet. Both techniques produce a large spread of the jet; however, the mass flow is intermittent in the latter case while in the former it is steady.

The present work was initiated to investigate the vane excited technique in detail to study the rate of spread under different conditions of excitation. This research activity forms a part of the overall program to study the performance of an ejector with different mixing devices.

## 2. Experimental set-up

The experiments were conducted in a subsonic jet issuing from a 15 cm long straight rectangular nozzle of span 20 cm and of width (h) 2 cm (aspect ratio of 10). These dimensions were chosen to have a reasonably wide jet with high exit velocity to match the capacity of the centrifugal blower used in the system. In between the blower and the nozzle, a large settling chamber containing a honeycomb and a pair of fine screens was incorporated in order to remove unwanted fluctuations inside the nozzle. The exit velocity of the jet could be varied in the range of 5 to 60 metres/sec by a throttle valve provided at the entry of the blower. The Reynolds number ($R_h$) for the above velocities are 6000 and 72000 respectively.

A symmetric two-dimensional airfoil 2 mm thick, 20 cm long having a chord of 2 cm was placed 2 cm downstream of the nozzle exit as shown in fig. 1. The airfoil was oscillated in the vertical mode by an electromagnetic vibrator whose frequency could be varied from 2 HZ to 100 HZ with a maximum amplitude of 8 mm. Other

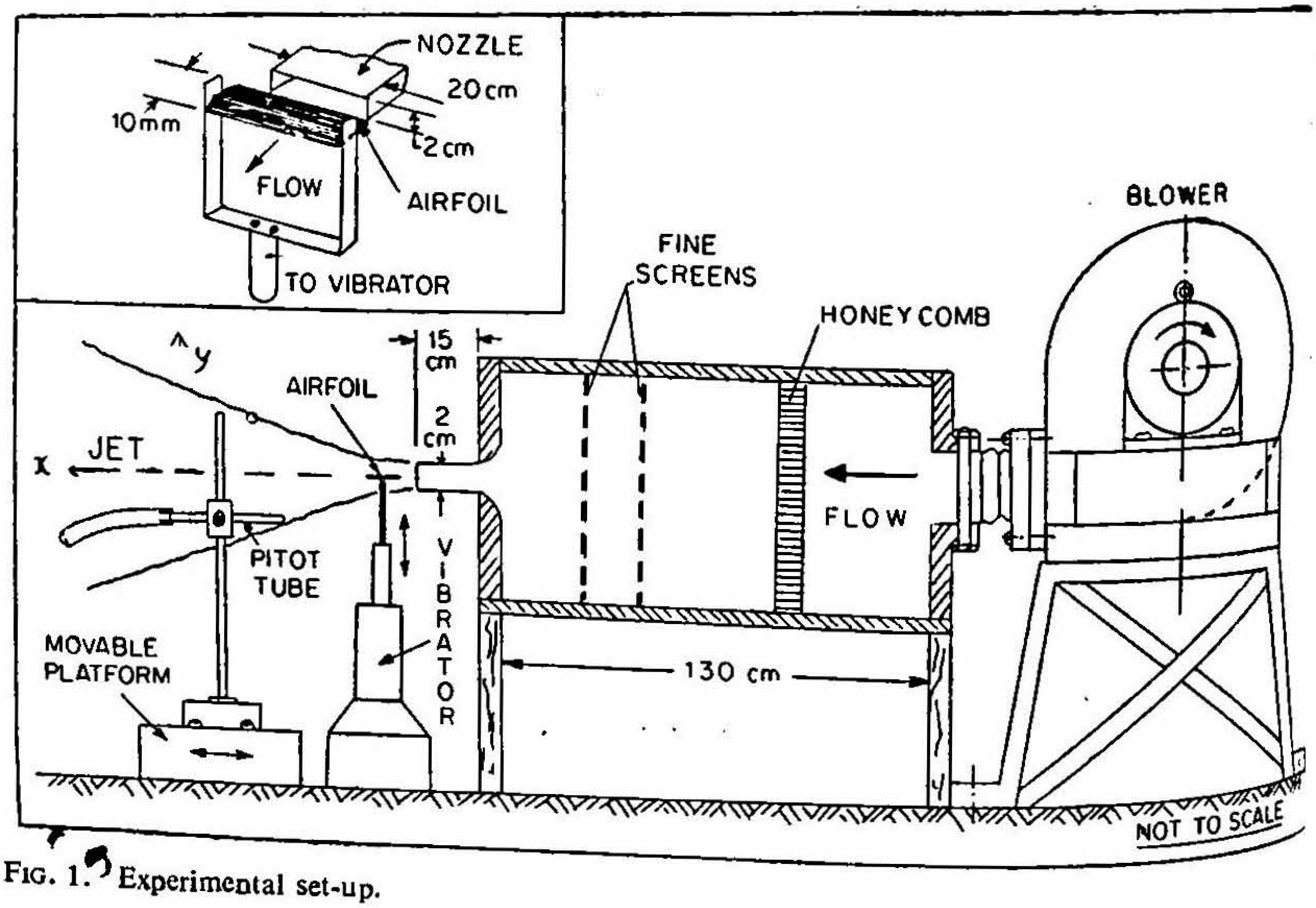


FIG. 1. Experimental set-up.

modes of oscillations were prevented by the use of a guide. In addition, the inertia of the vibrating unit was tailored to prevent resonance below 100 HZ.

The mean velocities were measured using a pitot tube having a shaped nose which had a tolerance for yaw up to 45° and the pitot pressure was read using a sensitive alcohol manometer. In addition to the pitot tube, a constant temperature hot-wire anemometer was also employed to measure mean velocities ; however, its use was restricted only to the first phase of the investigation for reasons stated in the next section. The hot-wire element was 2 mm long and fabricated using a five micron diameter Pt—Rh alloy wire and it was operated at an overheat ratio of 1·80.

## 3. Results and discussion

In the present investigation the experiments were restricted to the measurement of mean velocites across the jet at various locations along the *x*-axis. Initially both the hot-wire and the pitot tube were employed for this purpose. It was observed that there was quantitative agreement between the two measurements in a steady turbulent jet (fig. 2) but there was discrepancy in the case of excited jet especially at large distances downstream of the nozzle (fig. 3). In all the experiments the hot-wire recorded equal or higher velocity than the pitot tube. Similar observation has been reported by Simmons *et al*[1] in their investigation on jets using oscillating vanes. The reason for this discrepancy even though precisely unknown could be generally attributed to the frequency response characteristics of the instruments. Specific corrections could not be applied to improve the results. As a conservative measure, the velocities recorded by the pitot tube alone were used for the purpose of analysis in this investigation.

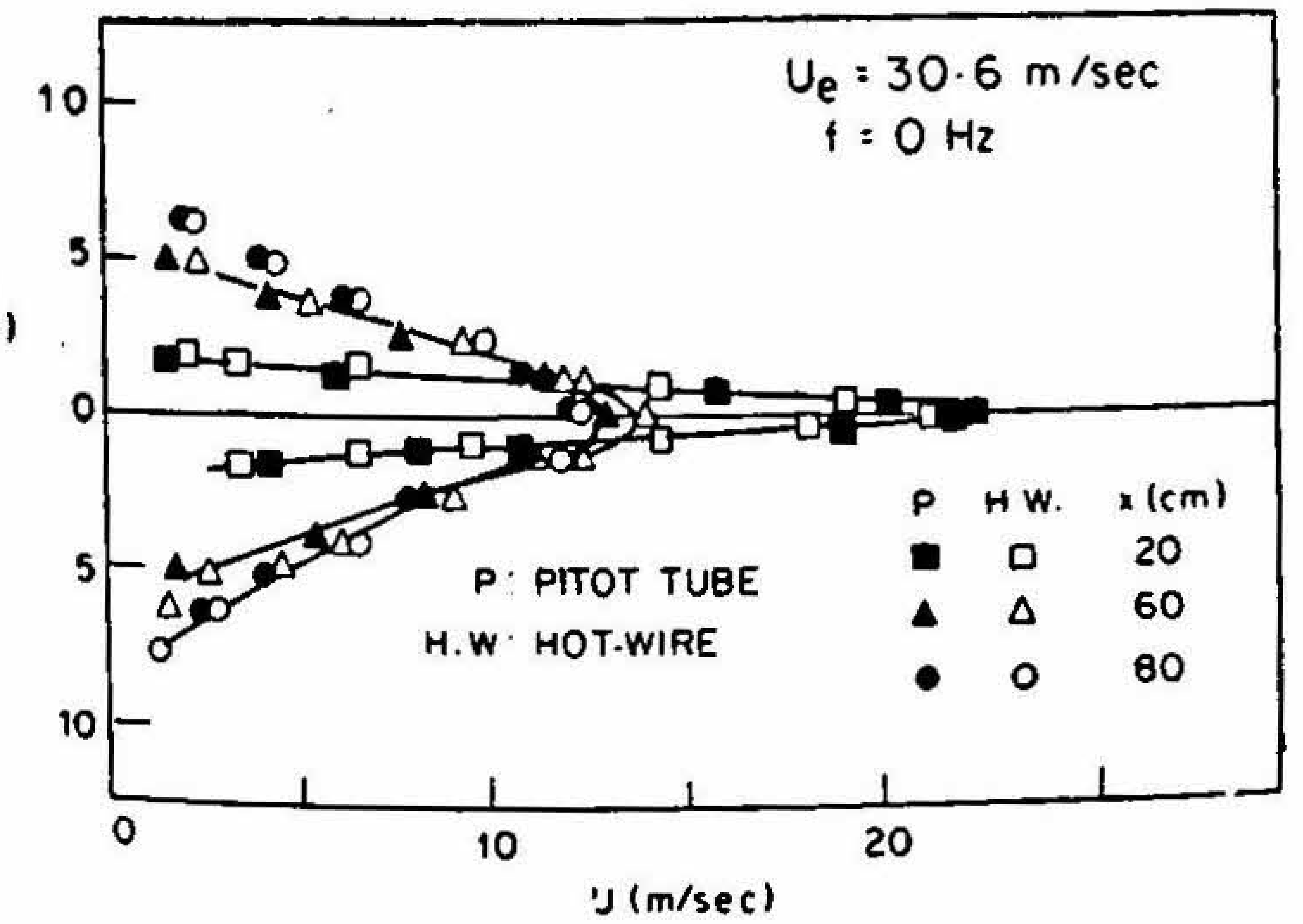


FIG. 2. Mean velocity profiles measured with hot-wire and pitot tube in a steady jet.

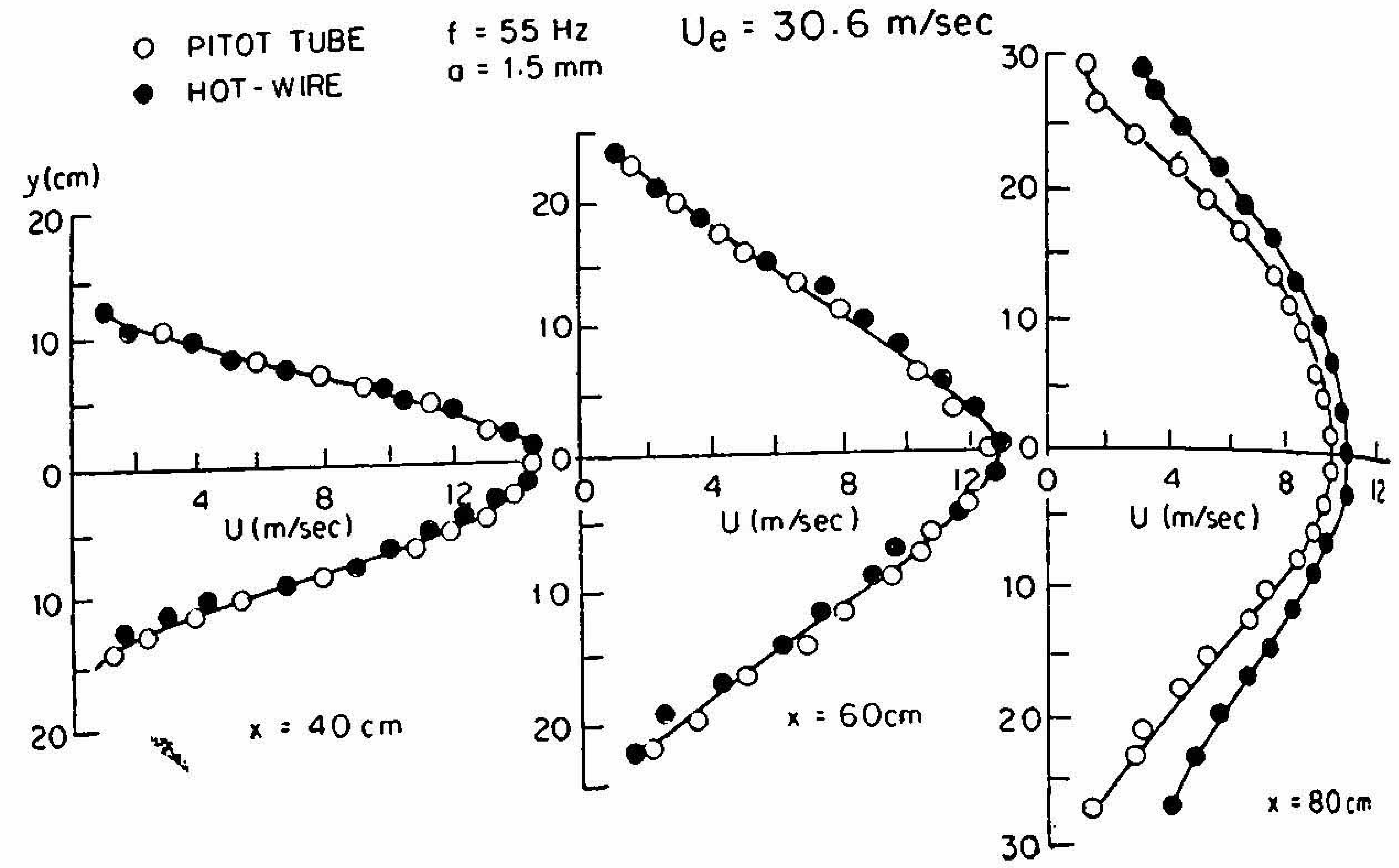


FIG. 3. Hot-wire and pitot tube measurements in an excited jet.

In order to examine the acceptability limit of the results using pitot tube measurements an estimate of the errors was made. For this purpose the pitot tube was clamped to the electromagnetic exciter and placed in the centre line of the jet 2·5 cm away from the nozzle. The pitot tube was vibrated at various frequencies and amplitudes. The experiments were repeated for different exit velocites and the results are shown in figs. 4*a* and *b*. At $U_e$ of 62 m/sec the pitot readings were insensitive to frequency whereas at lower velocities both the frequency and amplitude of oscillation had

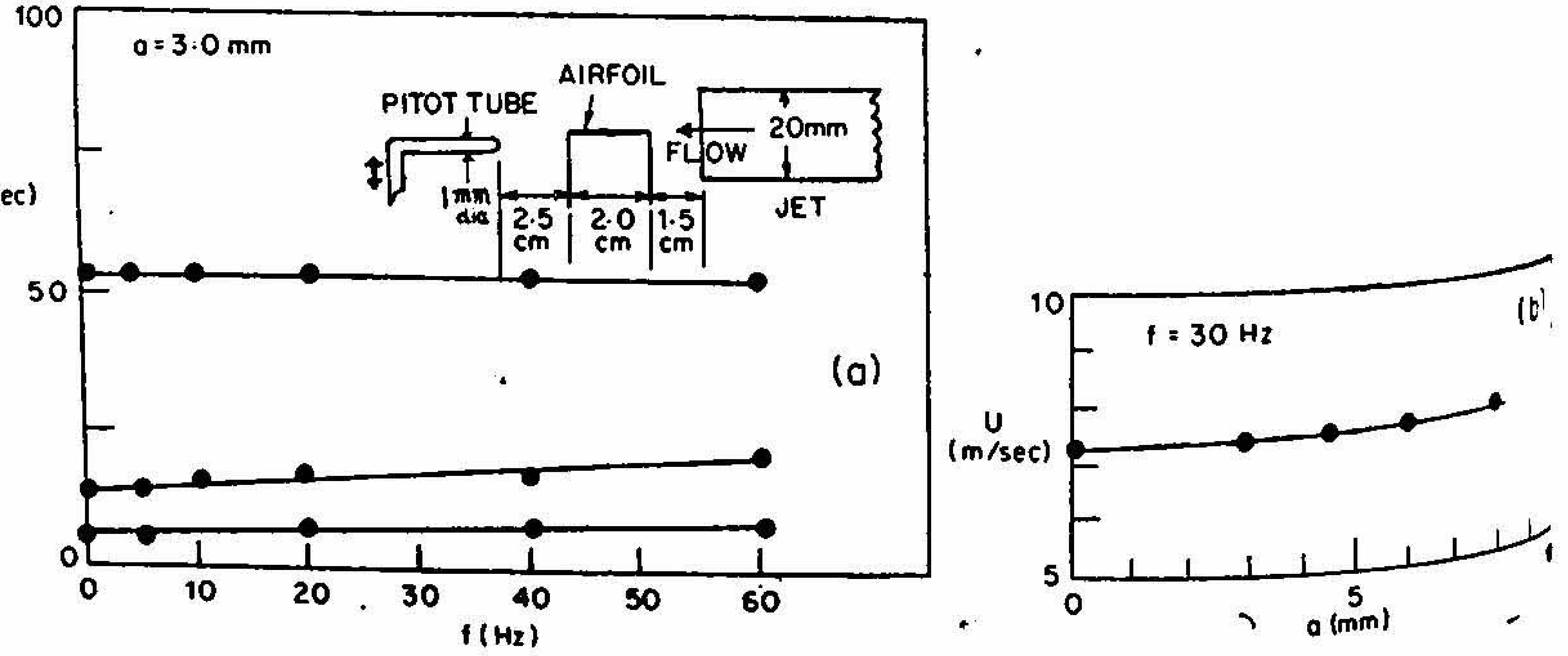


FIG. 4. Effect of frequency on pitot tube measurements.

combined effect on the velocity measurements. It is estimated, based on the above data, that the maximum error in the velocity measurements is about 6%.

The mean velocity profiles were measured downstream of the oscillating airfoil under different conditions varying (a) the frequency, (b) the amplitude of the oscillations and (c) the exit velocity of the jet. The experiments were classified under three categories A, B and C as follows.

### *Experiment A*

Measurement of mean velocity profiles along $x$ with an exit velocity of 30·6 m/sec and an amplitude of oscillation of 1·5 mm. The frequency of excitation was varied in steps from 0 to 10, 30, 50, 70 and 90 Hertz. The Reynolds number ($R_h$) of the flow was about 36000.

### *Experiment B*

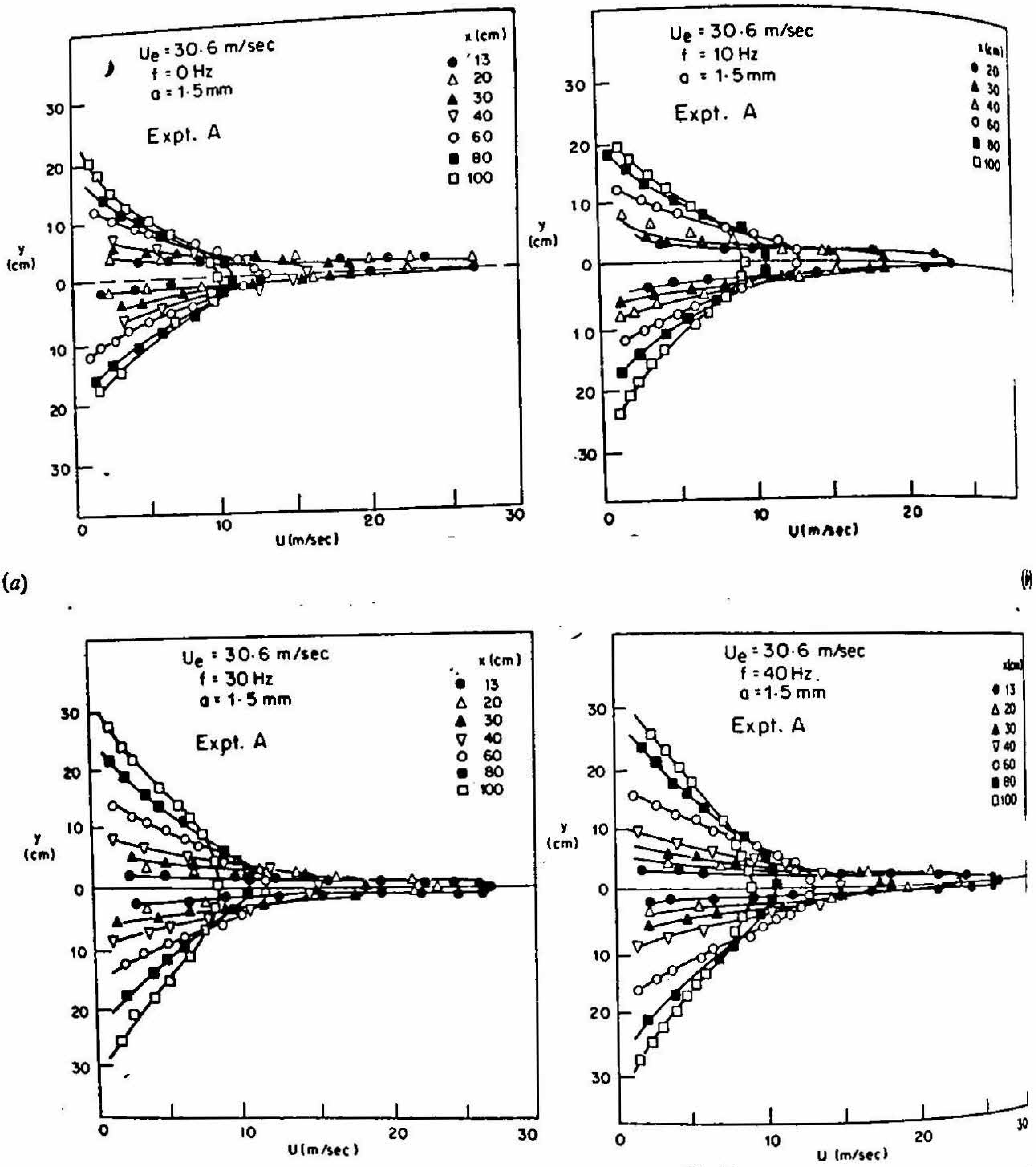
Mean velocity profiles were measured at $x/h = 30$ with the airfoil oscillating at 30 HZ. In this experiment the exit velocity as well as the amplitude of oscillation were varied. Four different exit velocities of 14·6, 30·6, 47·0 and 62·0 m/sec were used. The amplitudes were 0, 1·5, 3·6 and 8 mm.

### *Experiment C*

Measurement of mean velocity profiles along $x$ were made at a higher exit velocity of 62 m/sec. The airfoil was excited at 30 HZ with amplitude of oscillation at 0, 1·5 and 4 mm. The Reynolds number ($R_h$) of the flow was about 72000.

In all the above experiments the velocities were measured along the $x$-axis. Based on the data obtained from Experiments A, B and C, the growth of the jet as well as entrainment characteristics were estimated.

The mean velocity profiles corresponding to Experiment A are shown in figs. 5a to g. The exit velocity was 30·6 m/sec and the amplitude was maintained constant at 1·5 mm ($a/h = 0{\cdot}075$). At 10 HZ (fig. 5*b*) the spread of the jet was practically the same as that of the steady case up to $x/h = 40$ and slight increase was observed beyond this distance (fig. 5*a*). As the frequency was increased the spread was more conspicuous than the steady state, with larger spread at higher frequencies. Due to the limitations imposed by the electromagnetic exciter on the amplitude of vibration, the experiments could not be performed beyond 90 HZ. At this highest frequency the spread of the jet was quite appreciable (fig. 5*g*). The mean velocity profiles which were symmetric about the centre line at all other frequencies exhibited slight distortion in this case beyond $x/h$ of 40.0.

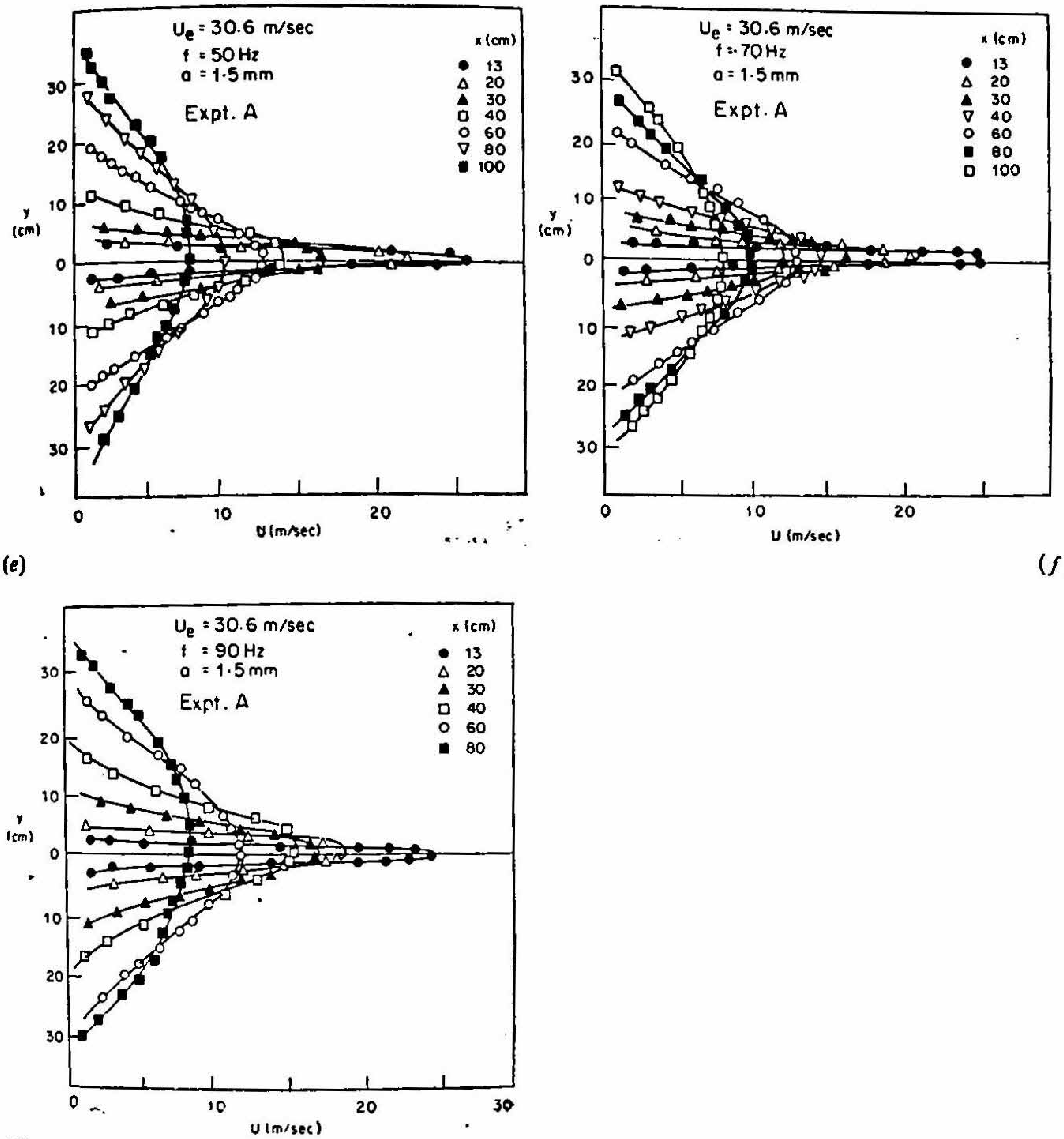


(a)

(c)

FIG. 5. Mean velocity profiles.

The investigations of Simmons *et al*[4] are similar to those of the present studies in several aspects ; however, a direct comparison could not be made because of difference in the mode of oscillation of the airfoil. In their set-up the airfoil was pivoted and subjected to a pitching mode of oscillation whereas in the present case it was operated under zero lift condition,



(e)

(f)

(g)

FIG. 5. Mean velocity profiles.

The variation of the centre line velocity ($U_m$) for all frequencies of excitation seems to follow a general pattern as that of a steady jet (fig. 6). For the case of a steady jet the results are in good agreement with those of a two-dimensional jet obtained by Collins *et al*[5]. The decay in ($U_m$) increases with frequency.

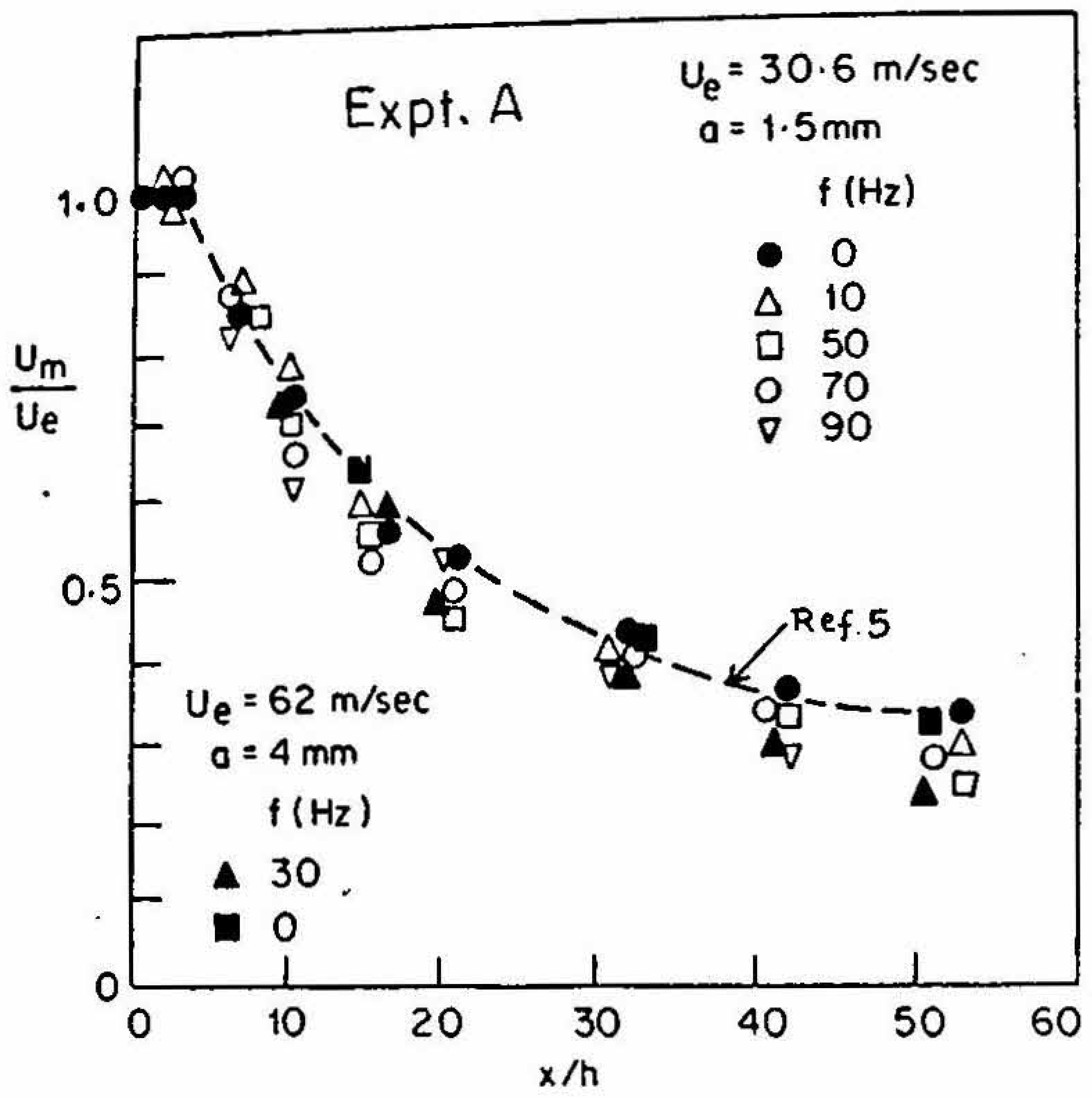


FIG. 6. Variation of mean velocity along the centre line.

A quantitative estimate of the spread of the jet was made by determining its half width ($\delta_{.5}$). The variation of $\delta_{.5}$ along $x$ is shown in fig. 7. Initially the growth of the jet is slow but beyond $x/h = 10$ it is faster. As a first approximation, the growth of $\delta_{.5}$ with $x$ could be assumed to be linear. The spread of the jet also increased with frequency.

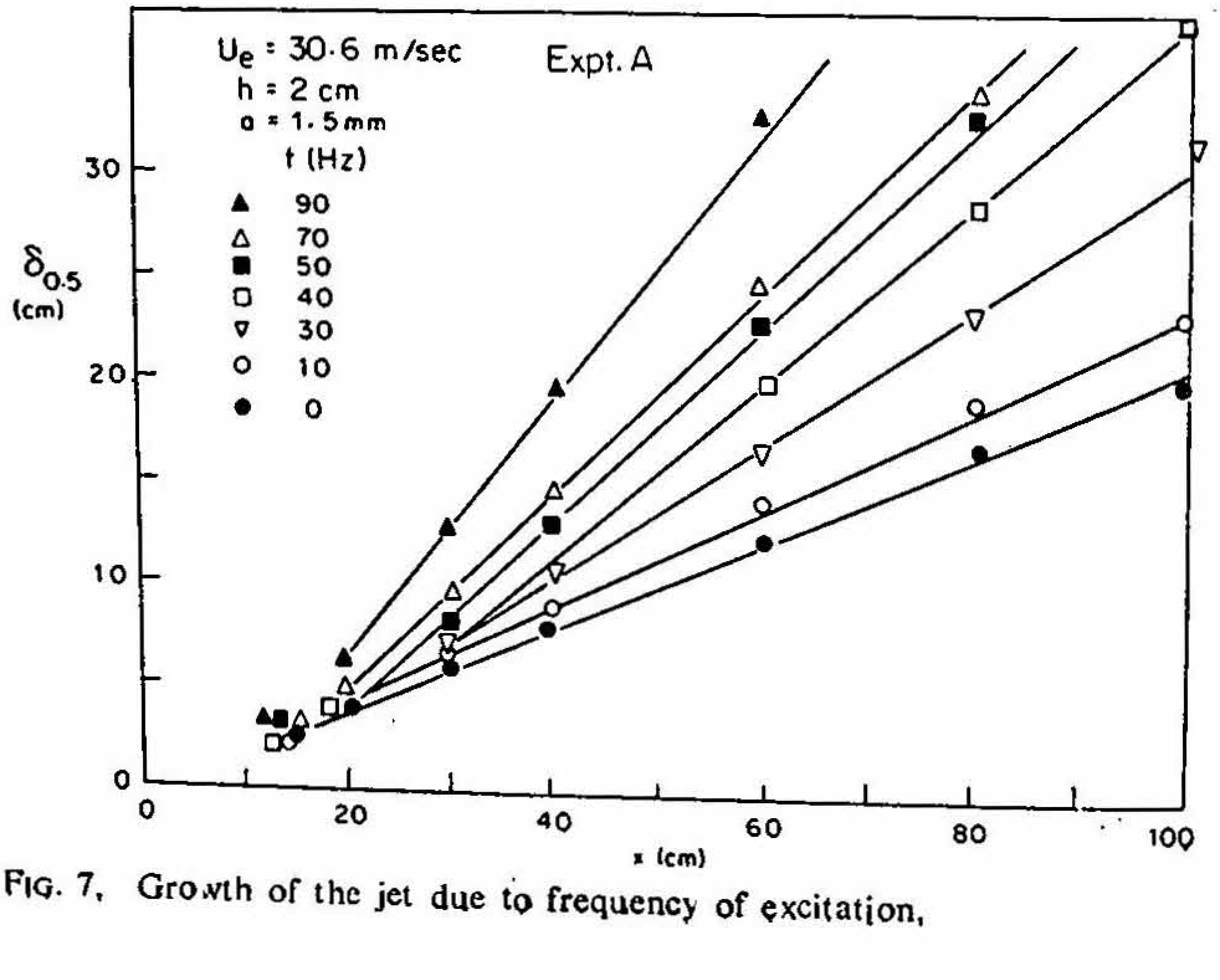


FIG. 7. Growth of the jet due to frequency of excitation.

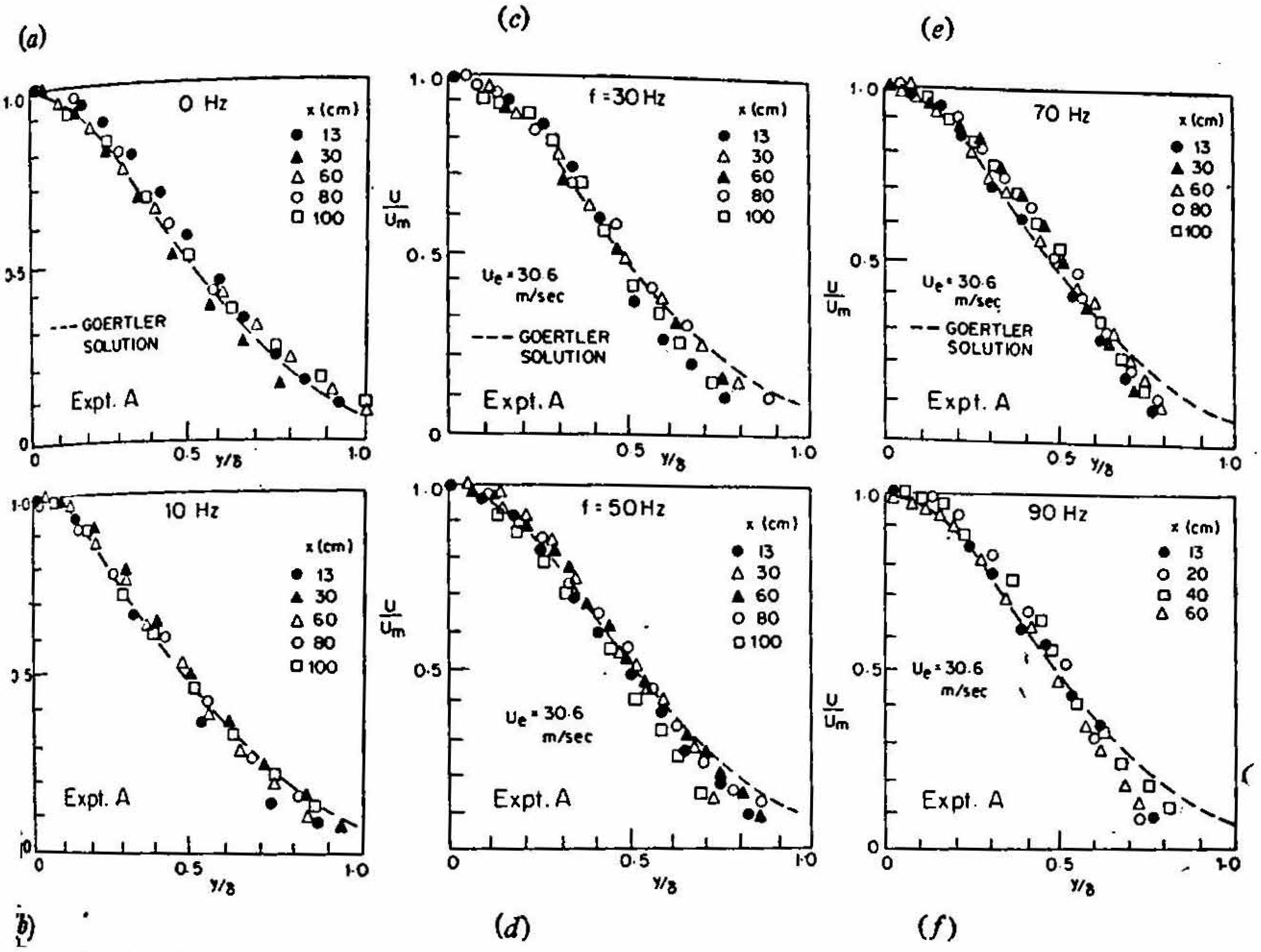


FIG. 8. Similarity in mean velocity profiles.

The mean velocity profiles of Experiment A were examined for similarity by plotting them in the non-dimensional form with the half width of the jet and the centre line velocity as length and velocity scales (figs. 8*a* to *f*). For the steady case the profiles follow Goertler's[7] similarity solution for a two-dimensional jet. The jets with excitation also exhibit similarity; however, they differ from that of the steady case predominantly in the outer region of the flow. Based on the above observation it could be concluded that even for an unsteady jet the mean velocity profiles could be described with a unique set of velocity and length scales similar to a steady jet. However, the relationship might be different for each case.

The rate of mass flow increased significantly with the frequency of excitation (fig. 9). The value of entrainment ratio ($Q/Qe$) reached a maximum value of 5·5 at $x/h = 30$ in Experiment A for $f = 90$ HZ, an increase of nearly 2·5 times when compared to the case $f = 10$ HZ. $Q$ and $Q_e$ are the volume rates of flow at any station $x$ and $x = 0$ respectively and were estimated by integrating the mean velocity profiles. The variation of $Q/Q_e$ with $x/h$ follows different patterns for each exci-

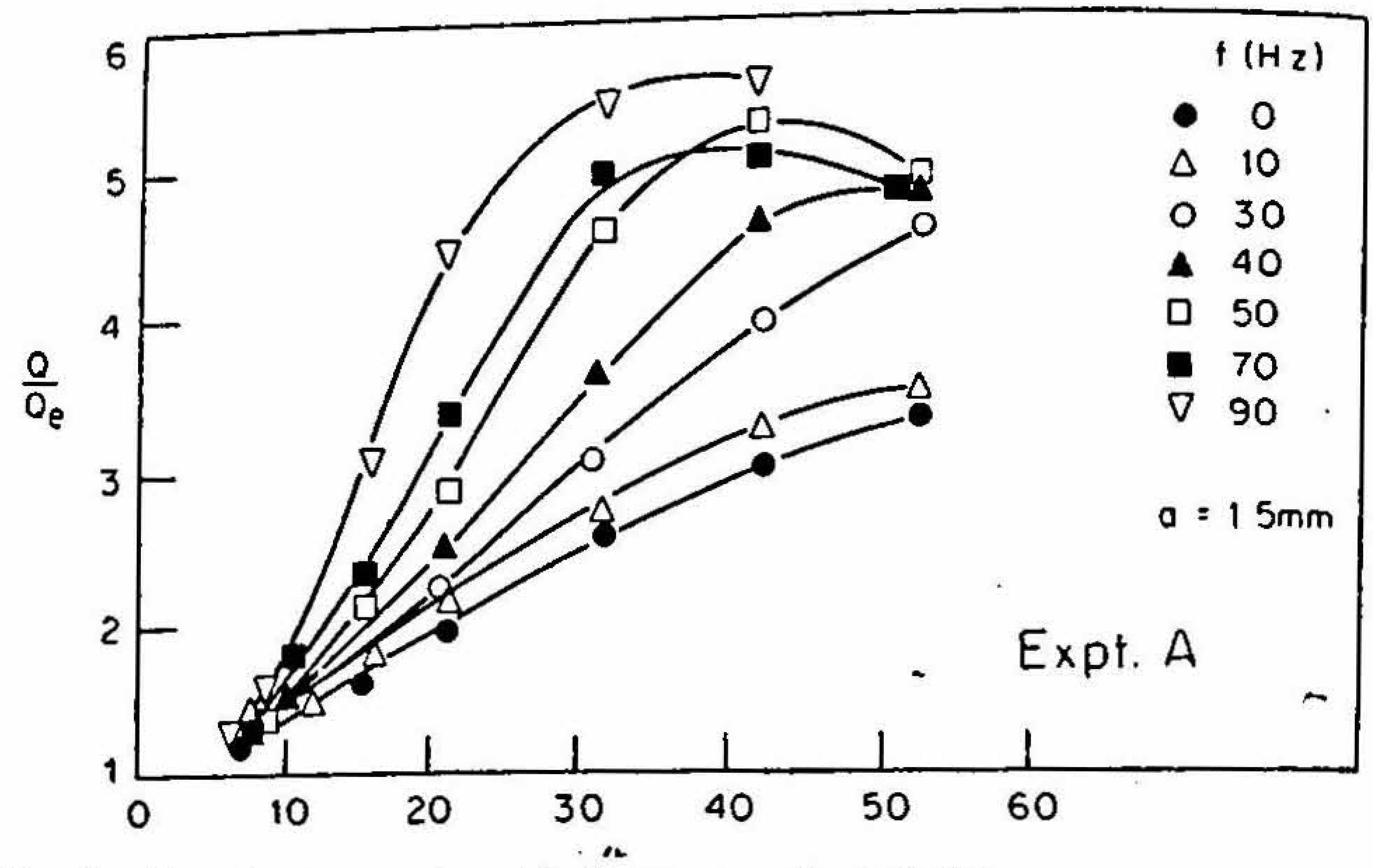
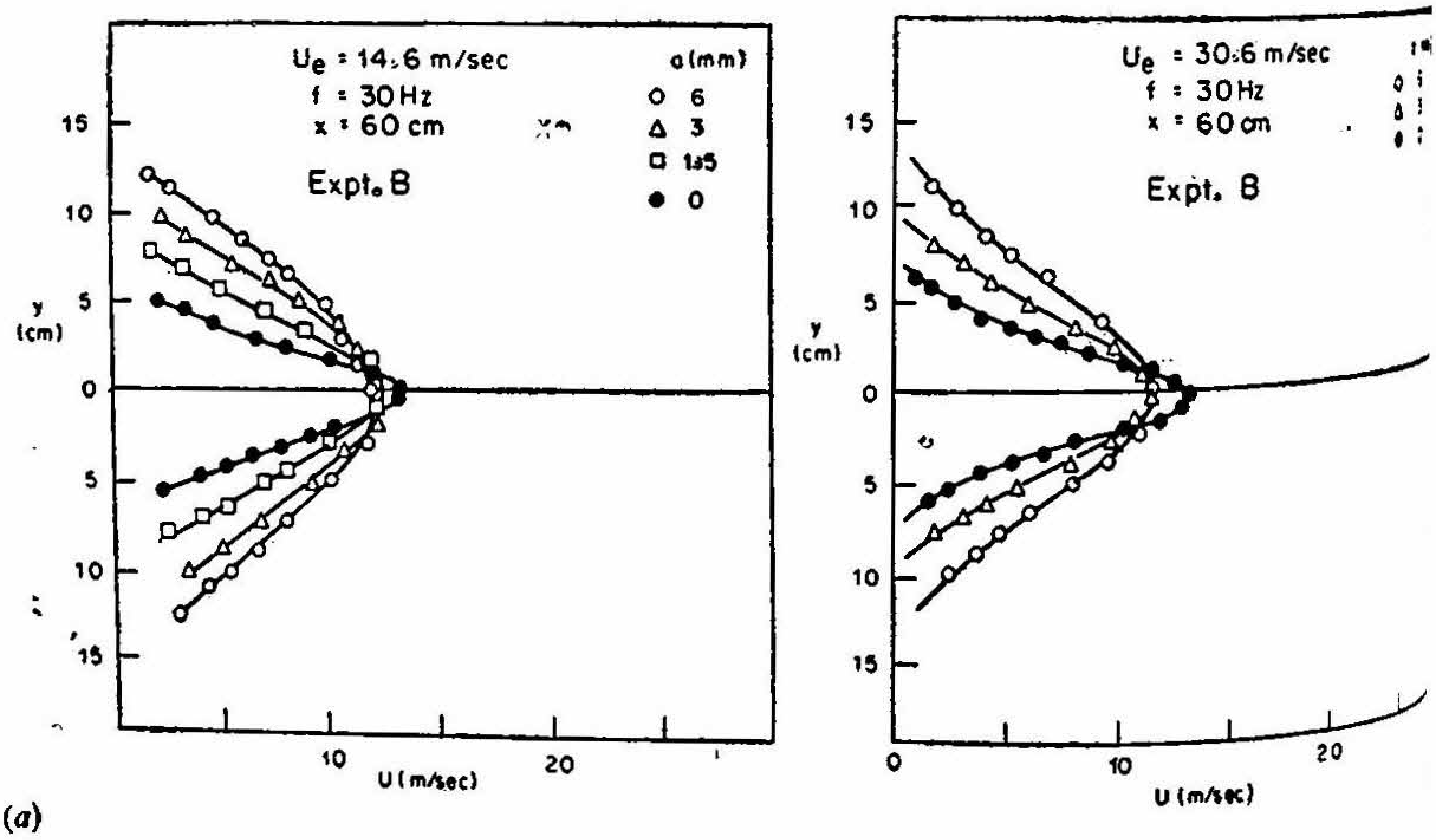


Fig. 9. Entrainment ratio with frequency of excitation.

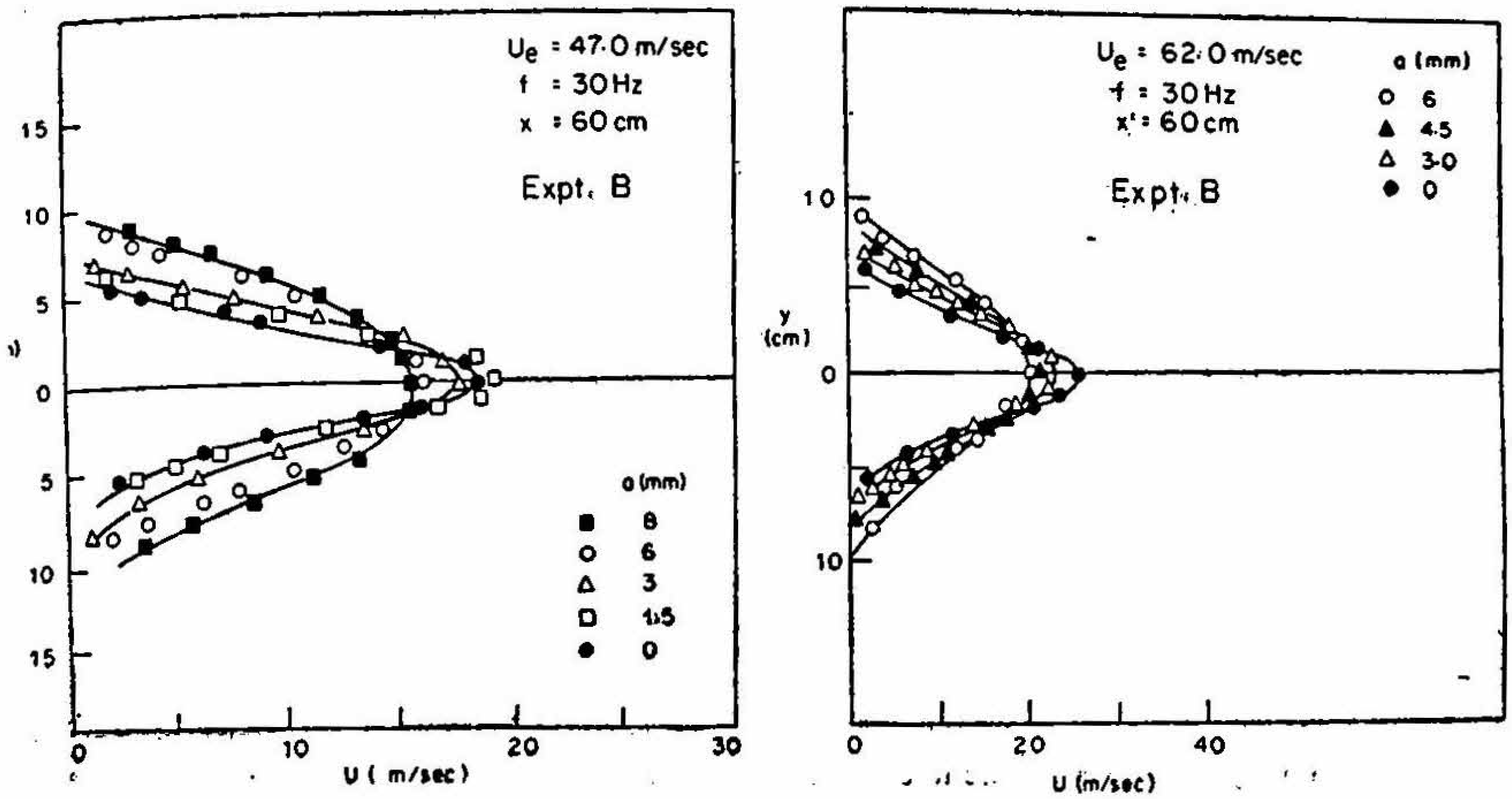
tation frequency. For the steady jet $Q/Q_e$ increases linearly with $x/h$ whereas f frequencies greater than 40 HZ there is rapid increase in the beginning, followed la by saturation.

The experiments in series B were designed to study the spread as well as the entrai ment at different amplitudes of excitation. An excitation frequency of 30 HZ w chosen and the mean velocities were measured at $x/h = 30$ for exit velocities of 14 30·6, 47 and 62 m/sec with the amplitude varied from 0 to 8 mm in discrete st (figs. 10*a-d*). A larger spread as well as an increased entrainment ratio w



(*a*)

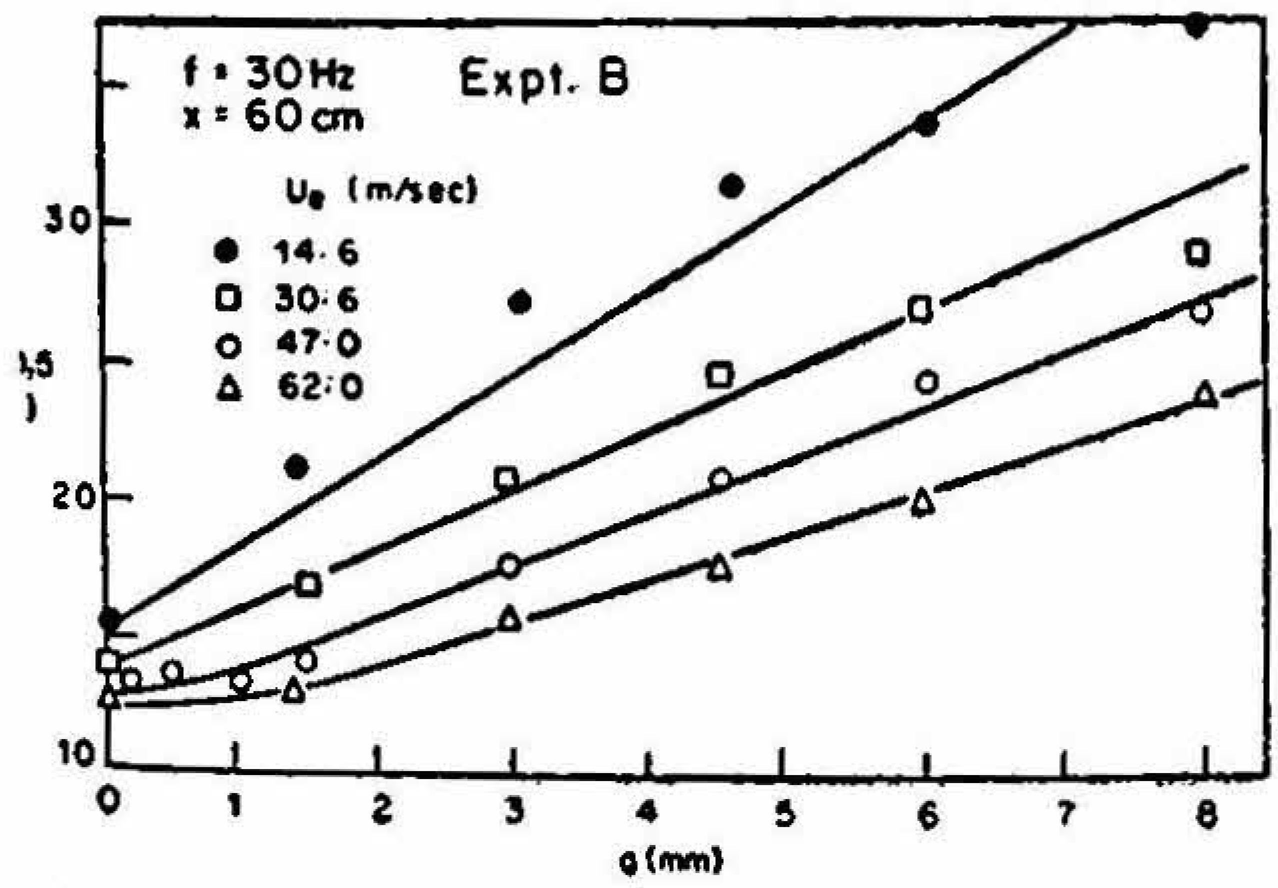
Fig. 10. Mean velocity profiles and amplitude of excitation.



(*d*)

. 10. Mean velocity profiles and amplitude of excitation.

served for lower exit velocities. Both the quantities increased with the amplitude excitation in a near linear manner except in the region where the amplitudes and ocities were small (figs. 11 and 12). In these experiments the quantity $Q/Q_e$ lows a definite trend for all the four exit velocities when the amplitude of oscillation nondimensionalised with frequency and exit velocity ($af/u_e$), (fig. 13). Since the ove observation pertains to a single $x$ location and frequency this trend cannot be nsidered as universal and calls for a closer examination.



11. Growth of the jet with amplitude of excita-

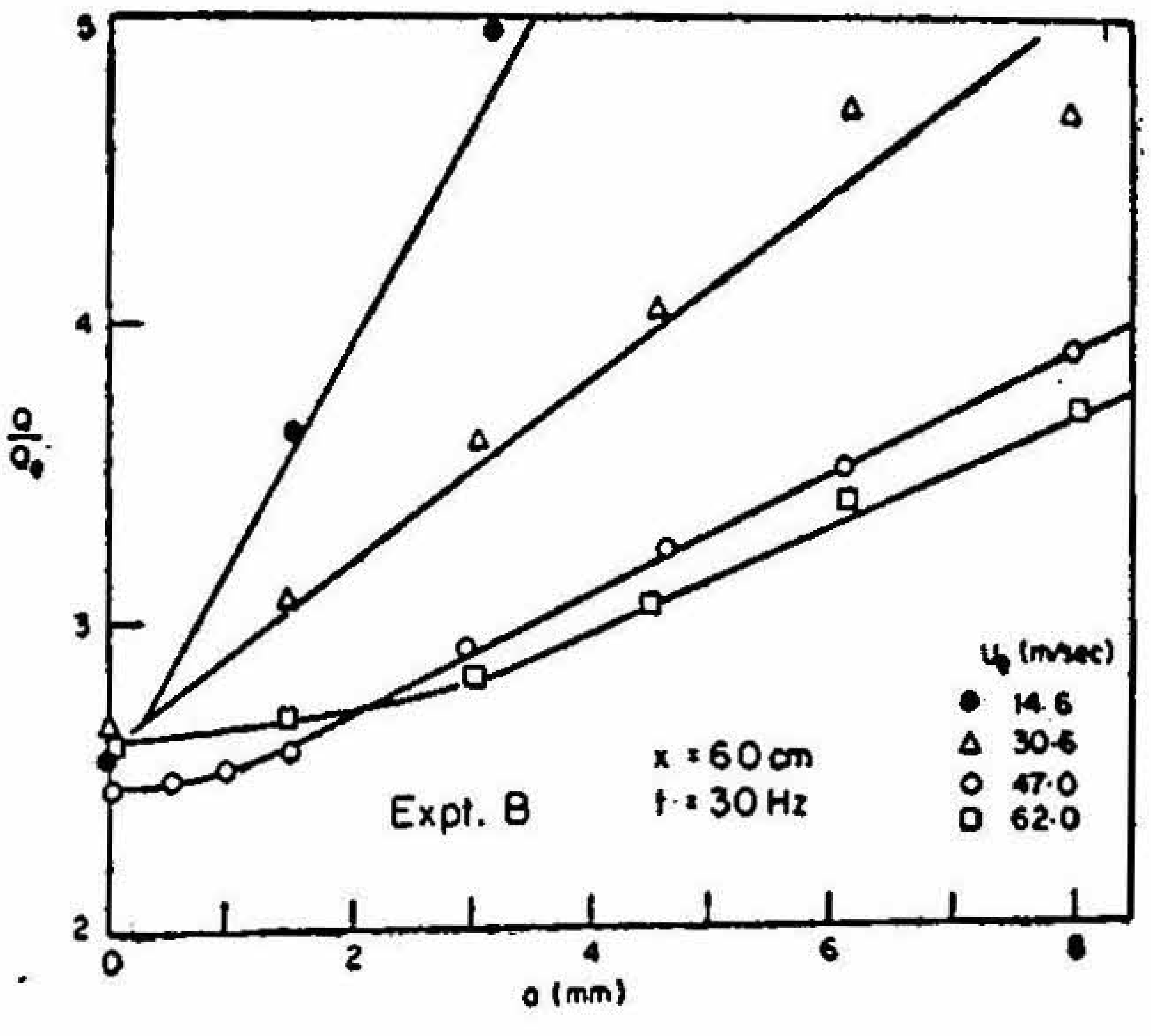


FIG. 12. Entrainment ratio with amplitude of excitation.

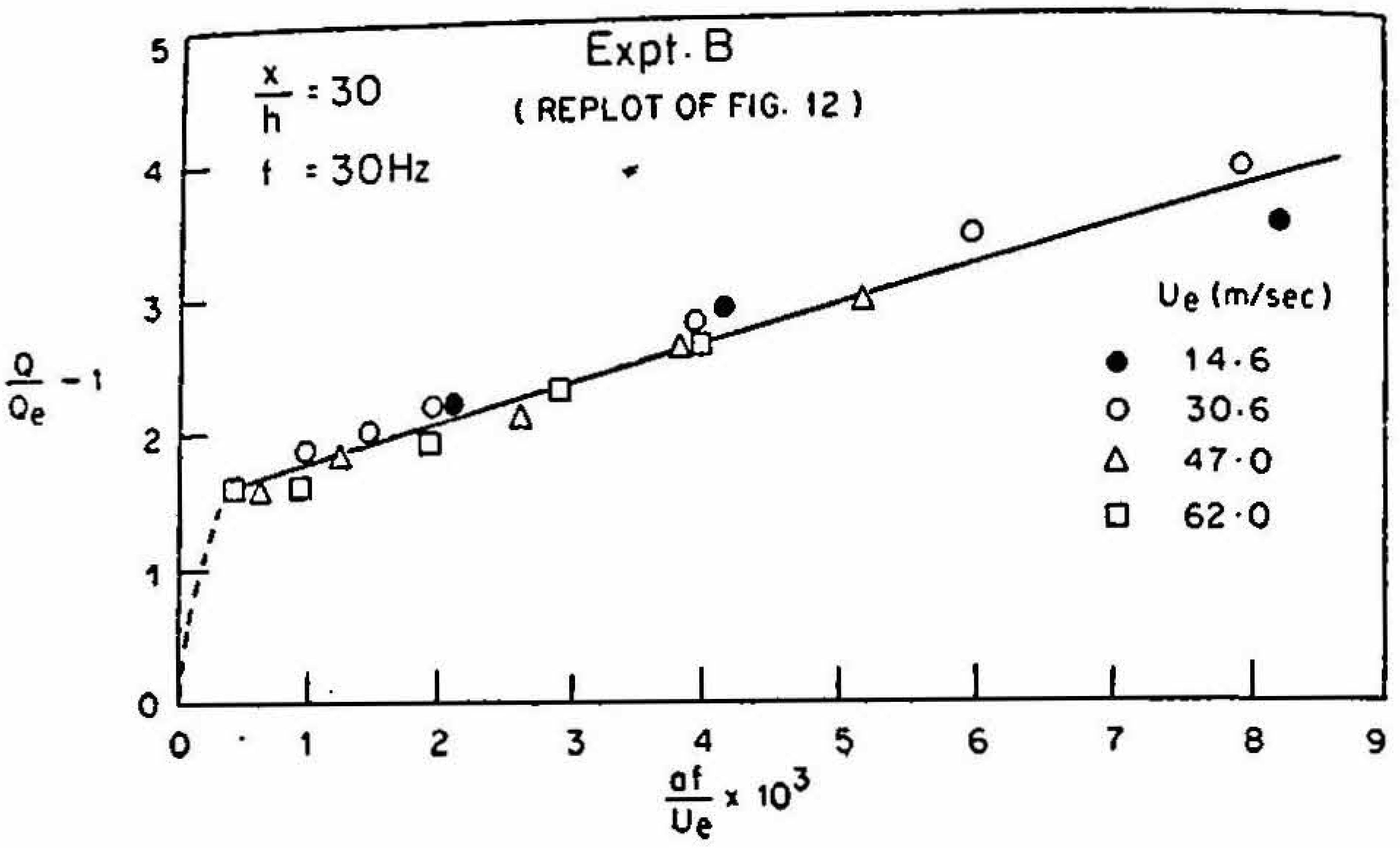
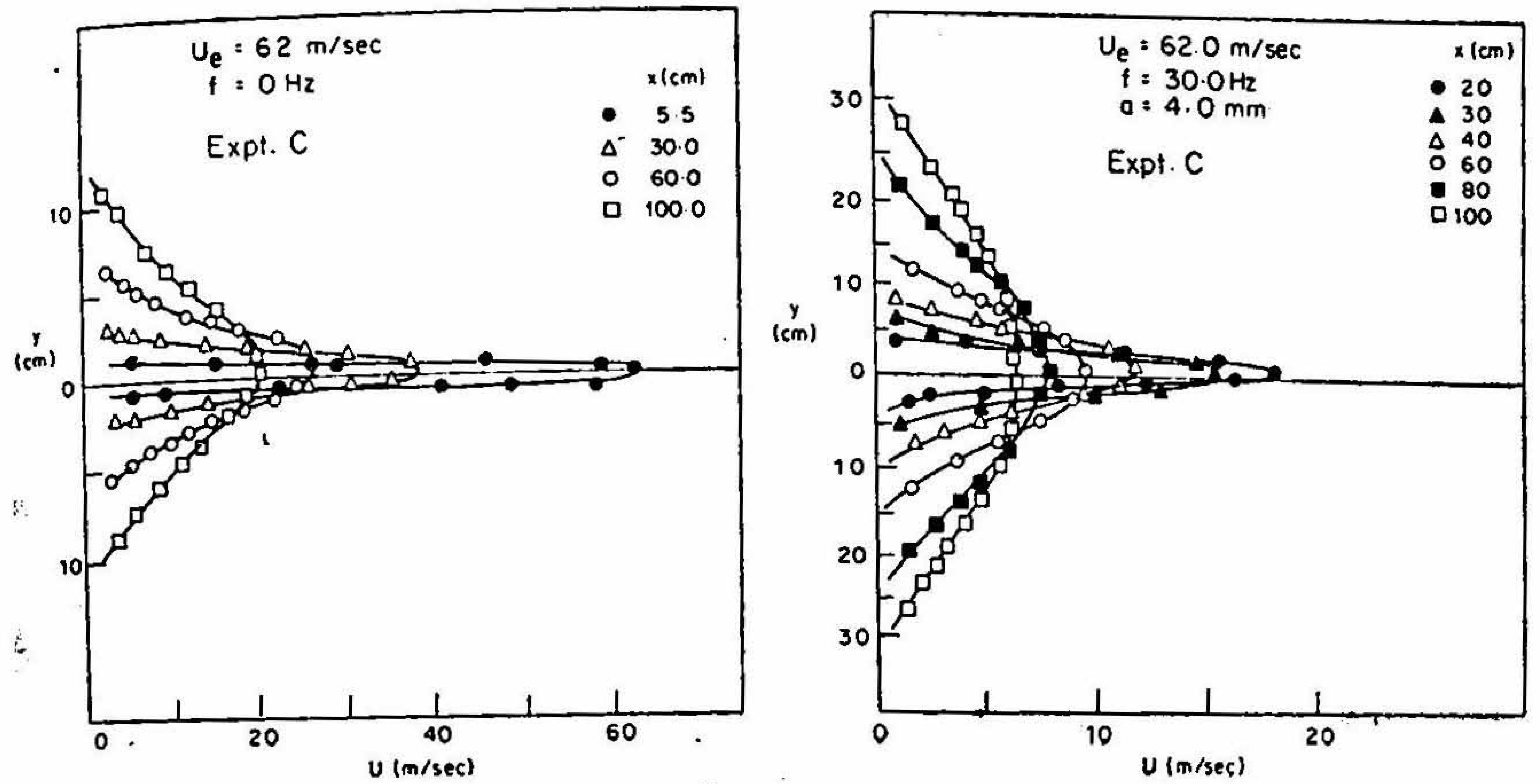


FIG. 13. Entrainment ratio at different exit velocities and amplitudes of excitation.

Experiment C was confined to the maximum exit velocity of 62 m/sec which could be obtained in this set-up. Initially the mean velocity profiles under steady conditions (fig. 14*a*) as well as at 30 HZ with an amplitude of 1·5 mm were measured. Both the profiles were almost the same and the effect of oscillation was found to be insignificant. The amplitude was increased to 4 mm to observe noticeable changes (fig. 14*b*). As in Experiment A the width of jet ($\delta_{.5}$) increased linearly with $x$ (fig. 15) after an initial development of $x = 30$ cm. The variation of entrainment ratio is shown in fig. 16.

In all the three sets of Experiments A, B and C the entrainment ratio ($Q/Q_e$) is found to be uniquely related with the growth of the jet. $Q/Q_e$ varies linearly with the half width of the jet with a slope nearly equal to 0.30.

To study the dynamics of the flow in the excited jet an understanding of the behaviour of the large scale structures is essential. In a steady two-dimensional jet the flow gets self-excited due to the large eddies that are formed near the exit region on account of instability[9]. These eddies which are orderly to begin with soon lose their identity and get merged with random turbulent velocity fluctuations. The excursion of these eddies could be seen as the interface in the outer part of jet. During this motion the flow imparts some of its momentum to the ambient fluid resulting in entrainment and thereby spreading of the jet. The amount of entrainment depends on the velocity and length scale as well as the orientation of the large scale structure to the flow. For a steady jet it has been observed that the eddies are formed at a well defined rate at a Strouhal number of about 0·30 based on the width of nozzle and the exit velocity[4].



(a) (b)

FIG. 14. Mean velocity profiles for $U_e = 62{\cdot}0$ m/sec.

In the case of an oscillating jet, certain changes in the formation of large scale turbulent structures could be expected. An examination of the hot-wire signals indicated the persistence of the forced excitation for considerable distances downstream (up to 15 to 20 h) whereas with the airfoil stationary no such periodicity was observed. The interface frequency was found to be the same as that of the excitation with the natural instability mode absent. Further downstream beyond $x/h = 20$ these periodic oscillations could not be recognised from the direct hot-wire traces ; however, they could be identified when processed using a tuned band pass filter and the signal was an order of magnitude weaker than the overall strength.

Based on the above observation one could conclude that excitation modifies the large scale motions, and hence the interface, thus having a significant bearing on the spread and entrainment characteristics of the jet. The rate of mixing should hence depend on the amplitude and frequency of excitation and this trend could be observed in the results of the present investigation. The low strength of the filtered signal beyond $x/h = 20$, suggests that the jet is reasonably free of flapping motions, which occur in fluidically oscillated jets[1]. In this respect the vane excited jet might find a more practical application in ejector technology.

## Conclusions

A two-dimensional jet was subjected to periodic oscillations by vibrating a thin symmetric airfoil in the potental core region. The excitation accelerated the spread of the

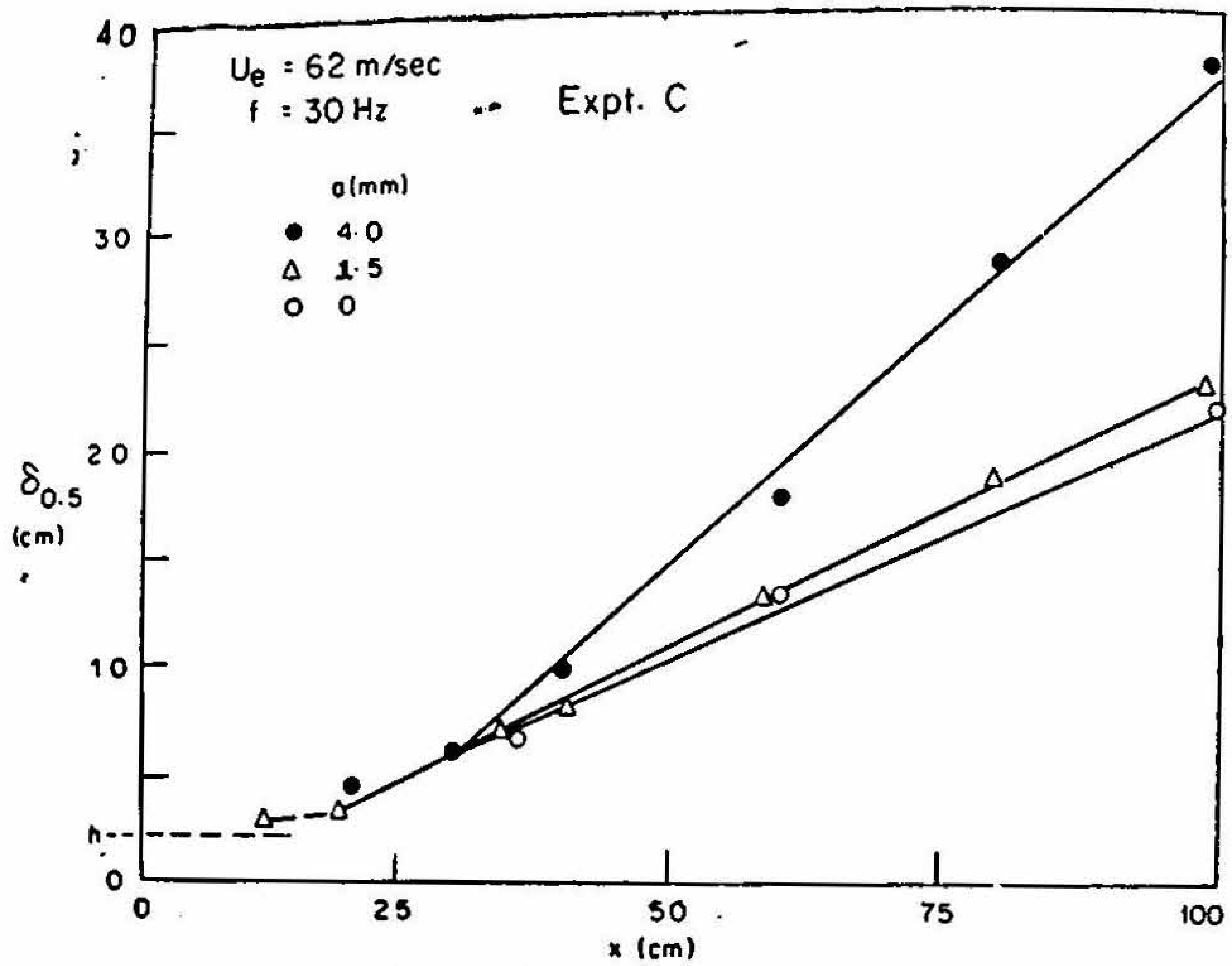


FIG. 15. Growth of the jet at $U_e = 62{\cdot}0$ m/sec due to amplitude of excitation.

jet with appreciable increase in entrainment. Both these quantities depended on the amplitude as well as on the frequency of vibration of the airfoil. The following trends were observed in the present investigation.

(*a*) The width of the jet ($\delta_{.5}$) increased linearly with distance ($x$) downstream the spread being more at higher frequencies for a given amplitude of oscillation of the airfoil and exit velocity.

(*b*) The decay of the centre line velocity was faster for an excited jet and depended on the strength of excitation.

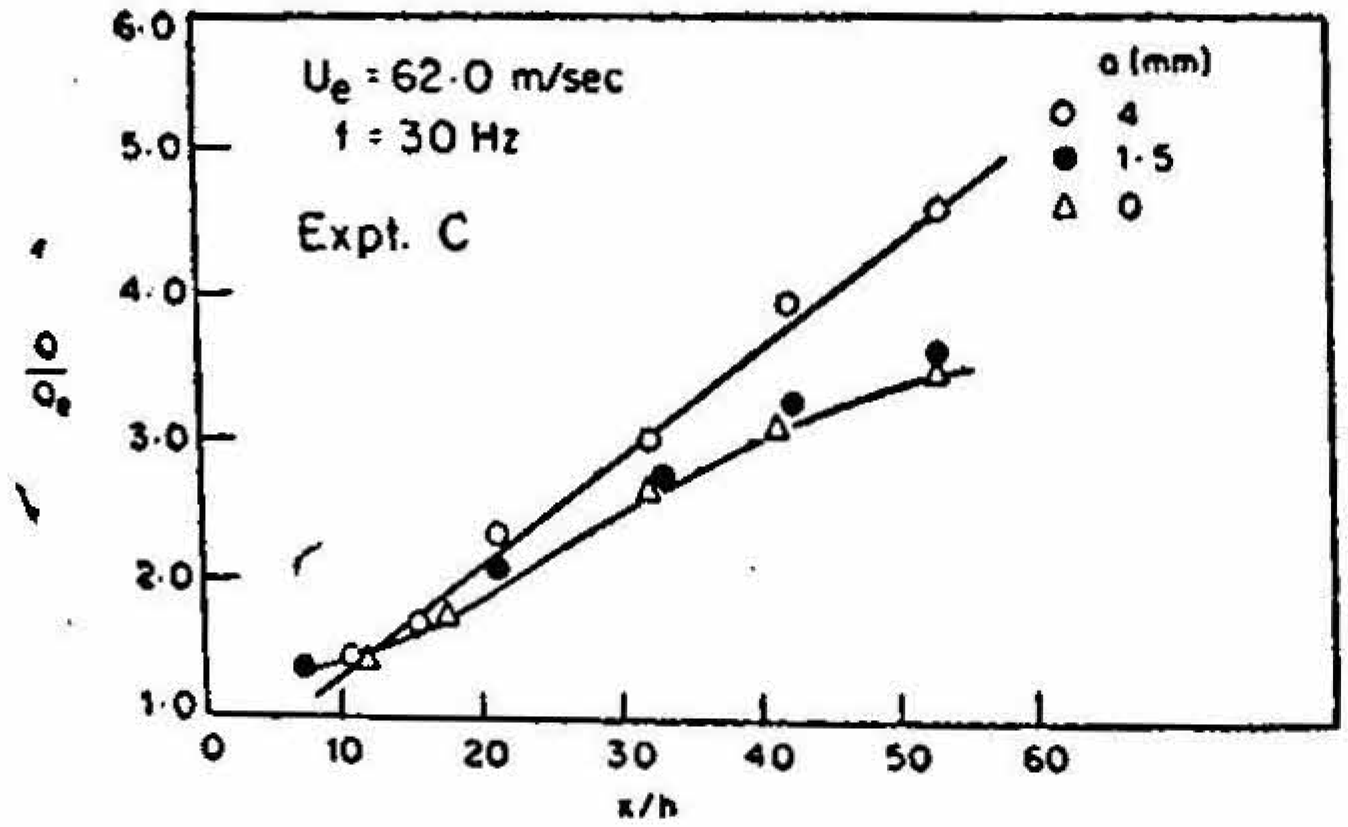


FIG. 16. Entrainment ratio for $U_e = 62{\cdot}0$ m/sec with amplitude of excitation.

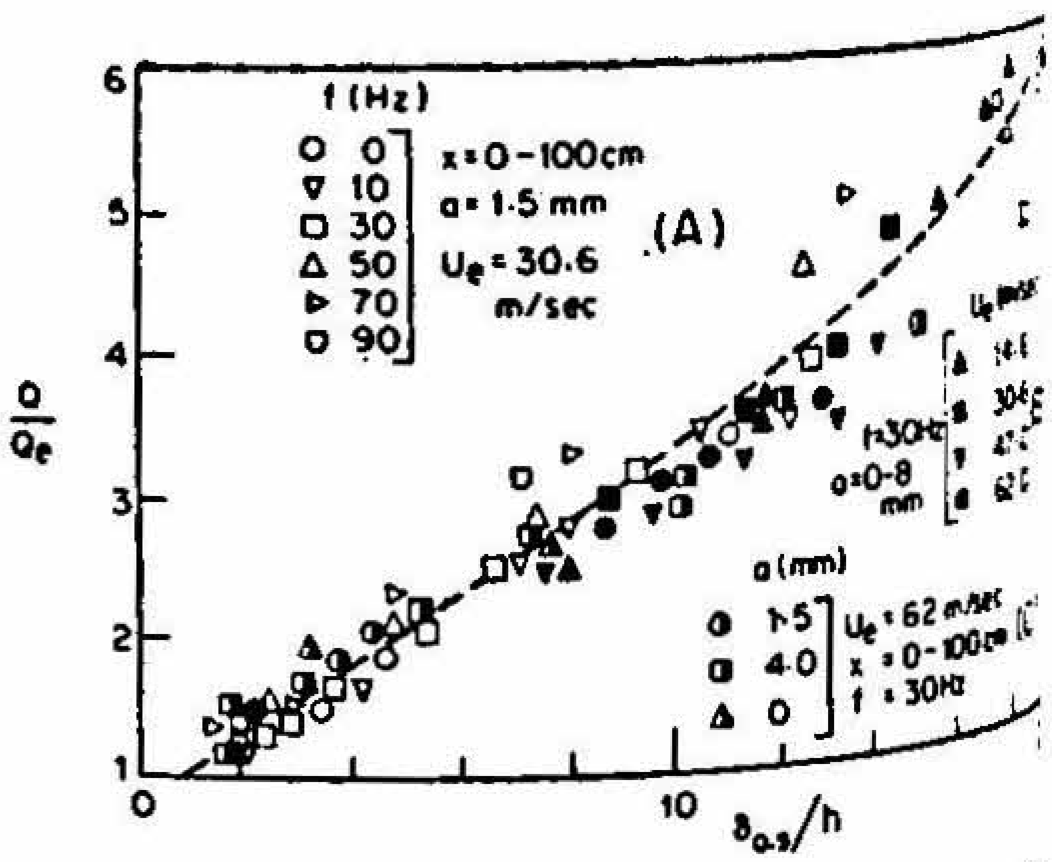


FIG. 17. Entrainment ratio with spread of jet.

(*c*) For a given frequency and exit velocity the width of the jet increased linearly with amplitude of excitation.

(*d*) Larger spread of the jet was observed at lower exit velocities ; that is, to have the same spread of the jet, stronger excitation is required at higher exit velocity.

(*e*) The entrainment ratio is dependent on both the frequency and amplitude of excitation as well as on the exit velocity of the jet.

(*f*) The width of the jet ($\delta_{.5}$) and the entrainment ratio were found to be related in the form $Q/Q_e = 0.3\ \delta_{.5}/h$.

## *Nomenclature*

$x$ = Longitudinal distance from the nozzle exit
$y$ = Coordinate perpendicular to $x$-axis along the width of the jet. $y = 0$ at the centre of the jet
$h$ = Width of the nozzle
$\delta$ = Total width of the jet based on $0{\cdot}05\ U_{max}$
$\delta_{.5}$ = Half width of the jet based on half of $U_m$
$a$ = Amplitude of vibration peak to peak
$R_h$ = Reynolds number $= h\,U_e/\nu$
$u$ = Local mean velocity
$U_e$ = Mean velocity at the exit
$U_m$ = Maximum mean velocity at the centre of the jet
$Q$ = Volume rate of flow $= \int_0^\delta u\,dy$
$Q_e$ = Volume rate of flow at exit
$f$ = Frequency of vibration

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