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Final Report

ACOUSTICS-TURBULENCE INTERACTION

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Chapter I

SUMMARY

This report summarizes our research funded by the 9-month grant NSG-1290, "Acoustics-Turbulence interaction in a Circular Jet." Introduction, description, and preliminary results of this study were presented at the Third Interagency Symposium on University Research in Transportation Noise, (Hussain and Zaman 1975), which should be consulted for these aspects of the study.

Research performed under this grant fall into two parallel but somewhat independent aspects of acoustics-fluid mechanics interaction. The original objective of the study was the large-scale coherent structure in the near field of a circular jet under controlled excitation, which constitutes the primary thrust of the report and is reviewed in Chapter II. A major part of the results in this topic was presented/published at the Symposium on Turbulent Shear Flow, held at the Penn State University (Zaman and Hussain 1977a). This paper contains the motivation, literature review and procedures, not discussed separately in Chapter II, and is included as Appendix A.

The ratio of the excitation frequency to the natural instability frequency of the initial axisymmetric free shear layer of the jet being an important parameter, an investigation of the instability frequency was undertaken. Careful measurements, revealed that the hot-wire probe itself can induce and sustain stable upstream oscillation of the free shear layer. The characteristics of the free shear layer tone are found to be different in many ways from the widely investigated slit jet-wedge edgetone phenomenon. The shear tone induced by a plane wedge in a plane free shear layer was then investigated in order to further document this phenomenon. The

eigenvalues and eigenfunctions of the tone fundamental show good agreement with the spatial stability theory. Chapter III gives a comprehensive summary of these results. Some preliminary results were presented as a short communication at the recent Symposium on Turbulence held at Berlin; this short communication is included as Appendix B (Zaman and Hussain 1977b).

Figures in each of Chapters II and III and Appendices A and B are grouped and numbered independently. Thus figure numbers in any of these four components refer to figures in the same component only. Accordingly, each of the four segments of this report contains its own reference list.

Chapter II

Organized Structure in the Circular Jet under Controlled Excitation

This study was first carried out by introducing periodic excitations of controlled frequencies and amplitudes in three circular air jets of diameters: 1 in; 2 in; and 3 in. Periodic excitations were introduced with the help of a loudspeaker attached to the settling chamber. The amplitude of excitation u'_e/U_e was usually 2% unless otherwise stated. The flow field was explored with a hot-wire anemometer.

The primary conclusions of this study are (see Hussain and Zaman 1975):

The jet turbulence intensity is strongly affected by small-amplitude periodic excitation, the extent of the modification depends on the non-dimensional frequency i.e. the Strouhal number. While no significant effect on the centerline mean velocity is discernible, integral jet measures like the mass flux, entrainment rate, jet diameter and momentum flux are noticeably influenced by the excitation.

For jets with initially tripped shear layers, the data (figure 1) essentially duplicates that of Crow and Champagne (1971). The $St_D = 0.3$ case shows the largest centerline turbulence intensity. The peak at this St_D is somewhat lower than that found by Crow and Champagne even though the agreement at $St_D = 0.6$ is much better (figure 2). One phenomenon observed by us but yet remains unexplained is the near-exit suppression of turbulence intensity; see figure 3. For initially untripped jet, the variation of the centerline longitudinal fluctuation intensity is shown in figure 4. Note that the intensity is highest at $St_D \approx 0.85$; at $x/D \approx 2$ the pulsated fluctuation intensity is about 5 times that for the unpulsated case. Note

that for $St_D \approx 1.6$ there is a pronounced suppression of the fluctuation intensity. At still higher Strouhal numbers there is no noticeable influence of excitation on the fluctuation intensity.

The large amplification of the fluctuation intensity at $St_D \approx 0.8$ is associated with vortex pairing. As we will show, the relative motions of two vortex puffs produce the large fluctuations. Figure 5 shows the oscilloscope traces of the centerline hot-wire signal at $St_D \approx 0.8$. All the traces have identical horizontal and vertical scales. Note the essentially sinusoidal signal in 5(a); the vortices then start to pair up, as shown in figure 5(b); figure 5(c) shows that the pairing process is well on its way. The alternate weak and strong peaks are consistent with our later visualization studies showing that during the pairing process a following vortex decreases in diameter and rushes inside the preceding vortex and then undergoes merger. During the rush i.e. acceleration of the second vortex, the centerline velocity becomes very large. Note that in figure 5(d) the signal is very large and is precisely at half the frequency of excitation. Further downstream, the signal shows initiation of transition following the peak velocity (figure 5(e)).

Transition occurs rather rapidly during the pairing process; this has been confirmed through visualization studies. The two vortices go around each other then undergo abrupt change to a single laminar vortex or undergo transition. Figure 6 shows the spectral evaluation during stable vortex pairing as a function of x . Note that the occurrence of the subharmonic indicates vortex pairing. The appearance of the higher harmonics occurs rather abruptly indicating rapid spectral evolution through transition.

After these preliminary conclusions, it was decided to rebuild the tunnel with a two-settling chamber arrangement. The primary motivation for

the change was to eliminate any asymmetry introduced by the loudspeaker. The loudspeaker is attached to the first chamber. The flow then goes through a contraction, the second diffuser, the second settling chamber and then the second nozzle. Nozzle configuration used is the cubic equation profile (Hussain and Ramjee 1976).

After the discovery that the $St_D \approx 0.8$ mode produces the largest velocity fluctuation amplification, it was apparent that the hot-wire at the centerline of the jet was too far to capture the foot-prints of the vortices in the shear layer near exit, and the possible shear layer vortex pairing. With this in mind, when the hot-wire was placed nearer to the free shear layer we were able to detect shear layer vortex pairing.

Figure 7 shows a variety of situations when shear layer vortex pairing occurs. Note that the excitation is at the second peak, the subharmonic being due to vortex pairing. Note that while the Strouhal number based on the diameter St_D has a large variation, the Strouhal number based on the free shear layer momentum thickness θ is about 0.011 for all the cases. Thus $St_\theta \approx 0.011$ is the Strouhal number for vortex pairing in the shear layer. Since we have observed pairing of vortex puffs, this would then suggest that there are two different modes of vortex pairing in a circular jet.

Figure 8a shows the jet response as a function of the exit velocity U_e . Note that the velocities producing peak fluctuations correspond to the two Strouhal numbers $St_D = 0.85$ and $St_\theta \approx 0.011$. Note also that most of the fluctuations at the peaks are due to the corresponding subharmonics.

Figures 8b, c show the jet responses as functions of jet speed for two different locations of the hot-wire. Note that in figure 8b the Strouhal number values of 0.011 corresponds to the second subharmonic only.

In figure 8c, the hot-wire being farther downstream, can detect three successive pairings in the shear layer. The Strouhal number based on the third subharmonic is 0.011.

These data indicate that vortex pairing in a circular jet is of bimodal nature; one occurs in the free shear layer near the exit and scales on the shear layer thickness and is appropriately termed 'the shear layer mode'; the other occurs farther downstream and scales on the jet diameter and is called 'the jet mode'. The former occurs at $St_\theta \approx 0.011$ while the latter occurs at $St_D \approx 0.85$.

In order to test this speculation, the jet response was determined as a function of the excitation frequency while keeping speed U_e and excitation amplitude constant (Figure 9). Note that due to apparatus limitations, continuous changes in excitation frequencies (i.e. the settling chamber cavity resonance frequencies) could not be achieved. Once again, note that the detected subharmonic rms intensity is largest at $St_\theta \approx 0.011$ and $St_D \approx 0.85$.

Figure 10 shows the summary of the jet mode and the shear layer mode of vortex pairing. Also shown is the constant frequency lines; that is, if the jet is excited at $f_p = 70$ Hz strong, stable vortex pairing will occur at $Re_D^{1/2} \approx 113$ and 170.

In order to further understand the shear layer mode, the downstream spectral evolution in the shear layer was studied at $St_\theta \approx 0.011$ with the probe at $U/U_e \approx 0.7$ (see Figure 11). While the higher harmonic components show considerable scatter due to their low amplitudes and due to background turbulence, the fundamental and the subharmonics show well-defined trends. The higher harmonics are merely results of signal distortion (due to saturation) and are thus not physically relevant to vortex size or spacing.

With increasing x , the fundamental grows due to instability of the shear layer and reaches saturation. Simultaneously, the growth of the subharmonic $u_f'/2$ which extracts energy from the fundamental produces decay of u_f' . The subharmonic again saturates and its energy is reduced by the growth of the second subharmonic producing $u_f'/4$ while the saturation of $u_f'/2$ produces its harmonic i.e. u_f' . Note that at $x/D \approx 0.25$ about 90% of the intensity is due to the subharmonic associated with pairing.

Figure 12 shows streamwise evolution of the subharmonic for excitations at different Strouhal numbers. Note that $St_0 \approx 0.011$ produces the largest amplitude subharmonic, confirming that $St_0 \approx 0.011$ is the 'preferred mode' of vortex pairing in the free shear layer.

The corresponding 'jet mode' of vortex pairing at different St_D is shown in figure 13. Note that $St_D \approx 0.85$ is the 'preferred mode' of vortex pairing in the jet mode. Note also that the low subharmonic at $St_D \approx 1.6$ indicates almost total suppression of vortex pairing.

Figure 14 gives the axial variations of the rms fundamental amplitude of the centerline turbulence intensity at different Strouhal numbers. Note that the fundamental intensity is the largest at $St_D \approx 0.3$ (confirming Crown and Champagne's data). However, if the total turbulence intensity is taken into consideration (see figure 15), the 'preferred mode' is $St_D \approx 0.85$ rather than $St_D \approx 0.30$ found by Crow and Champagne. The reason why they missed this is that they studied for St_D 's up to 0.6 only. Note the large suppression of both fundamental and total intensity at $St_D \approx 1.6$.

Figure 16 shows the various harmonics of the jet mode. Note that most of the fluctuations beyond $x/D \gtrsim 0.75$ is due to the subharmonic associated with vortex pairing motions.

Figure 17 shows that for three different initial conditions the jet mode subharmonics are identical. This contrasts the suggestion of Browand and Laufer (1975) that the eventual puff mode frequency is arrived at through successive pairings of the initial shear layer mode. Our data suggest that the jet mode is essentially independent of the shear layer mode. Smoke pictures at $St_D \approx 0.85, 0.3, 0.425, 0.6$ and 1.6 and $St_\theta \approx 0.011$ are respectively shown in figures 18-21. Note the clear evidence of jet mode of vortex pairing at $St_D \approx 0.85$ (figure 18a,b) while no pairing is evident at $St_D \approx 0.425$ (figure 19a,b) or at $St_D \approx 0.35$ (figure 20a) or 0.6 (figure 20b). Note also that while there is shear layer vortex pairing at $St_\theta \approx 0.011$ there is no jet mode of pairing (figure 21a). Figure 21b shows the case of $St_D \approx 1.6$ showing no vortex pairing. The flow visualization studies have confirmed that the subharmonic of the hot-wire signal is indeed associated with vortex pairing.

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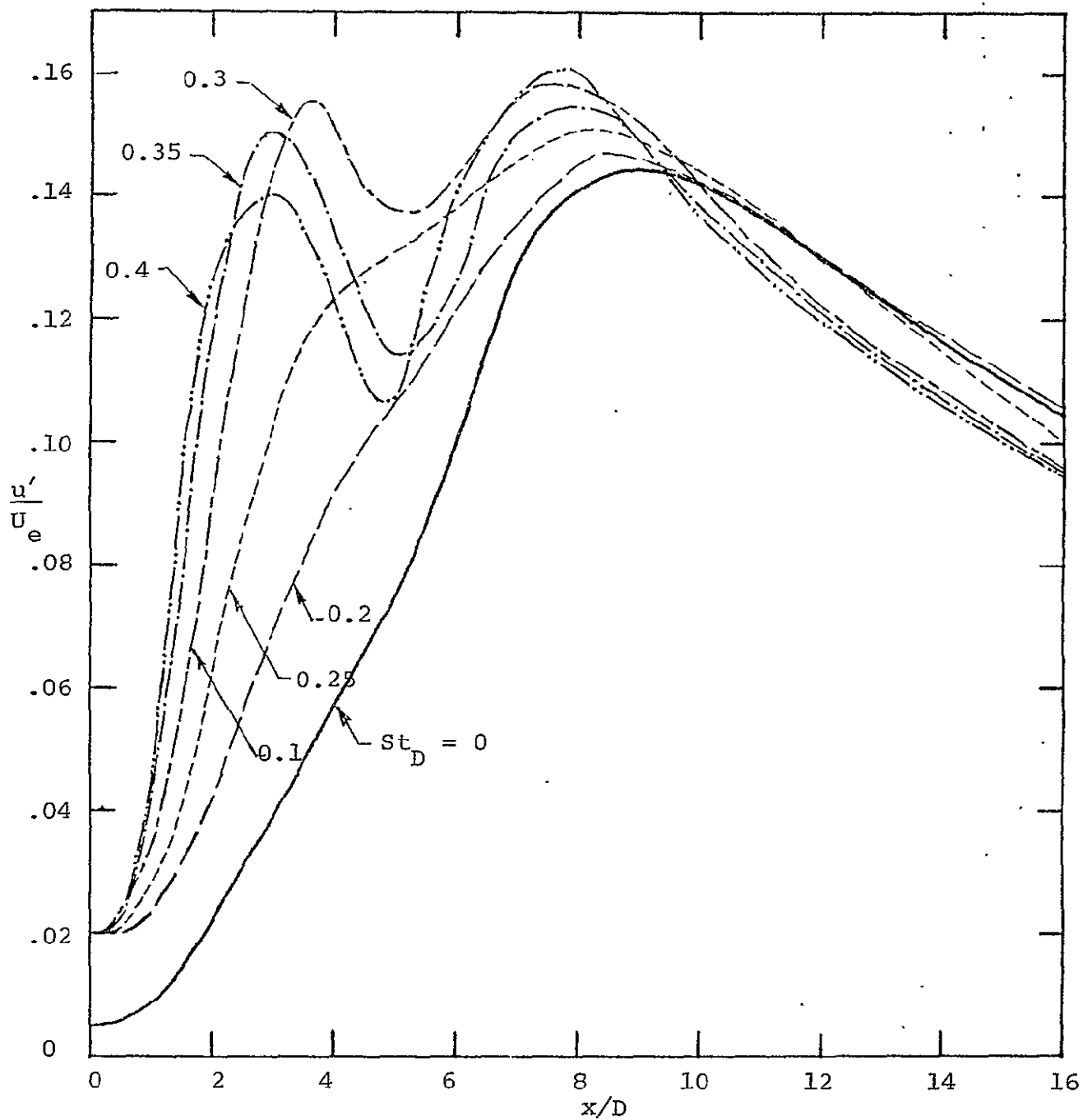


Figure 1

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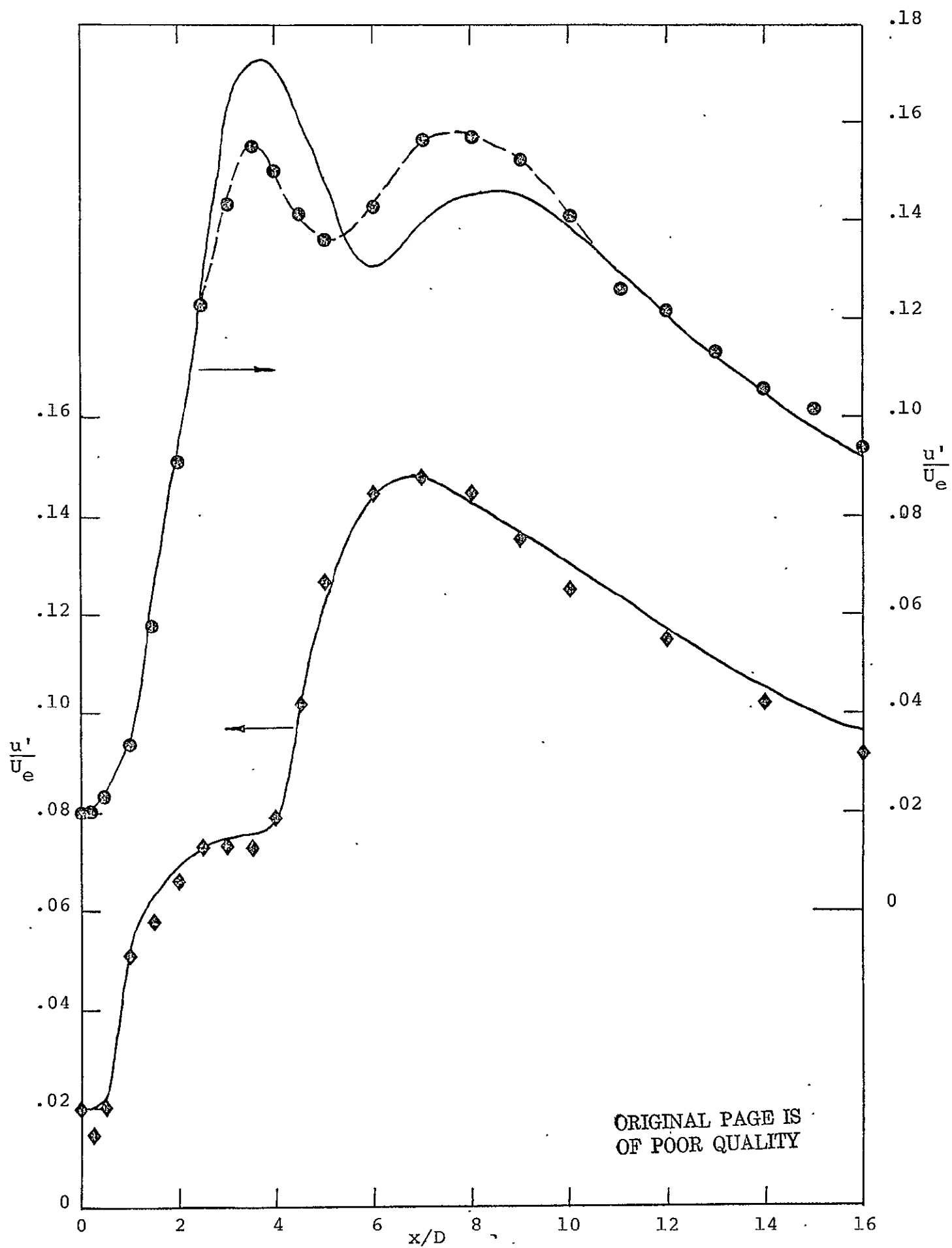


Fig. 2. u'/U_e - data for 3 in. tripped nozzle; $\bullet$ $St_D = 0.3$,
 $\blacklozenge$ $St_D = 0.6$. Crow and Champagne[1].

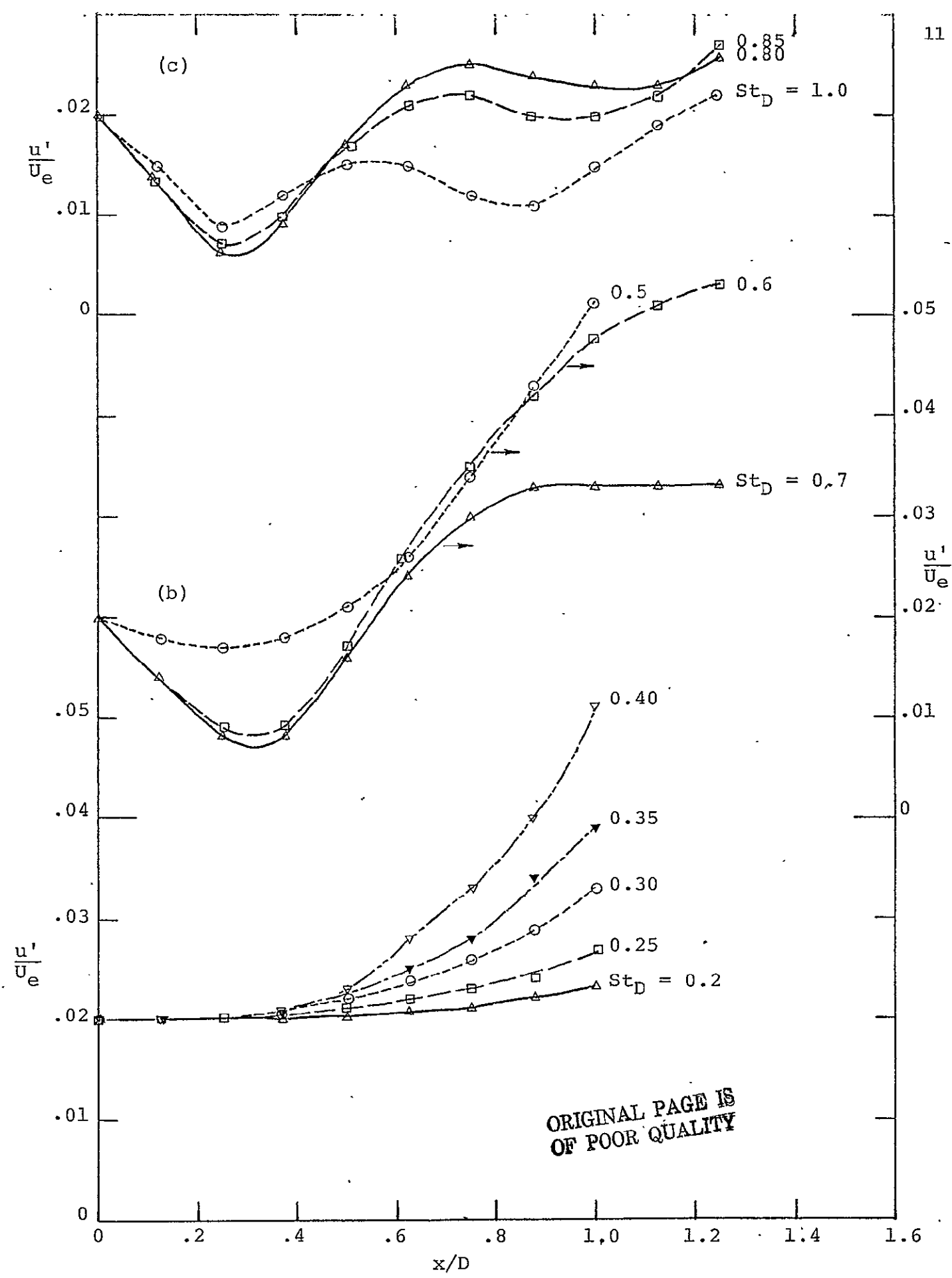
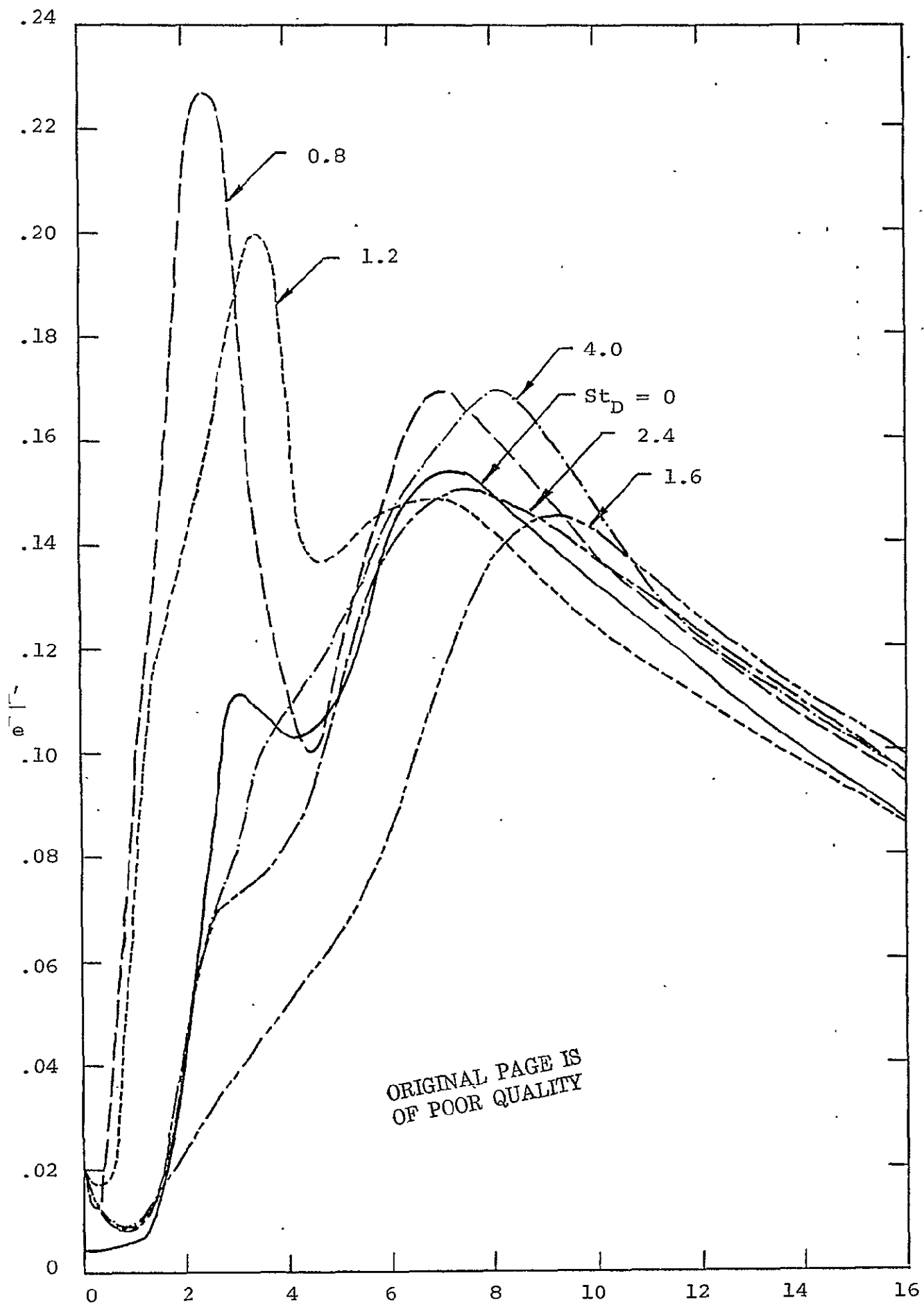
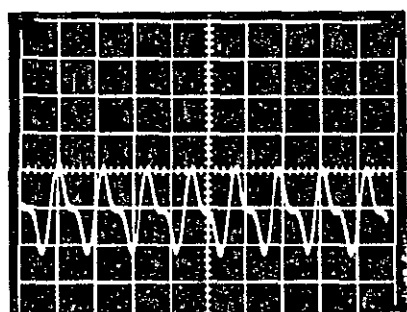


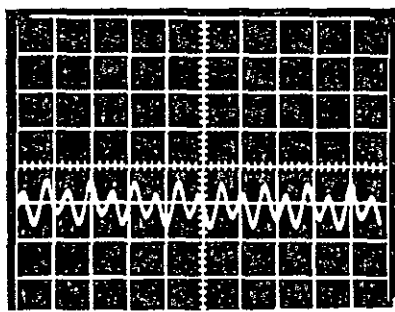
Fig. 3. Near exit turbulent intensity data for the 3 in. dia. tripped nozzle at different Strouhal numbers, St_D .

Figure 4

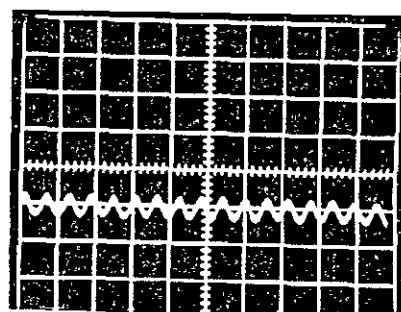




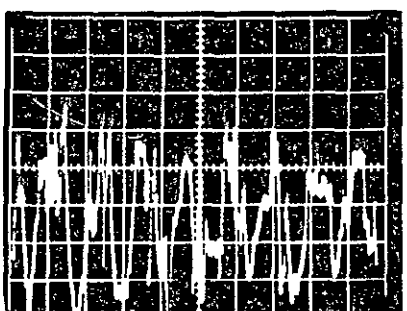
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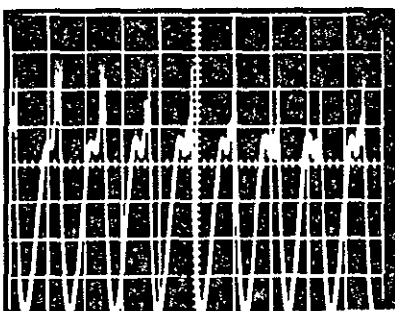
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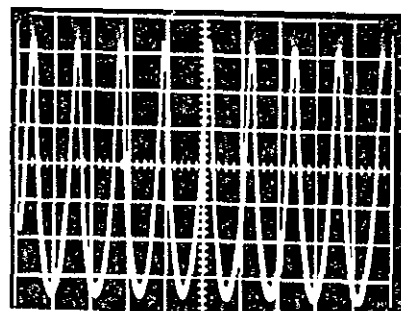
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(d)

Figure 5

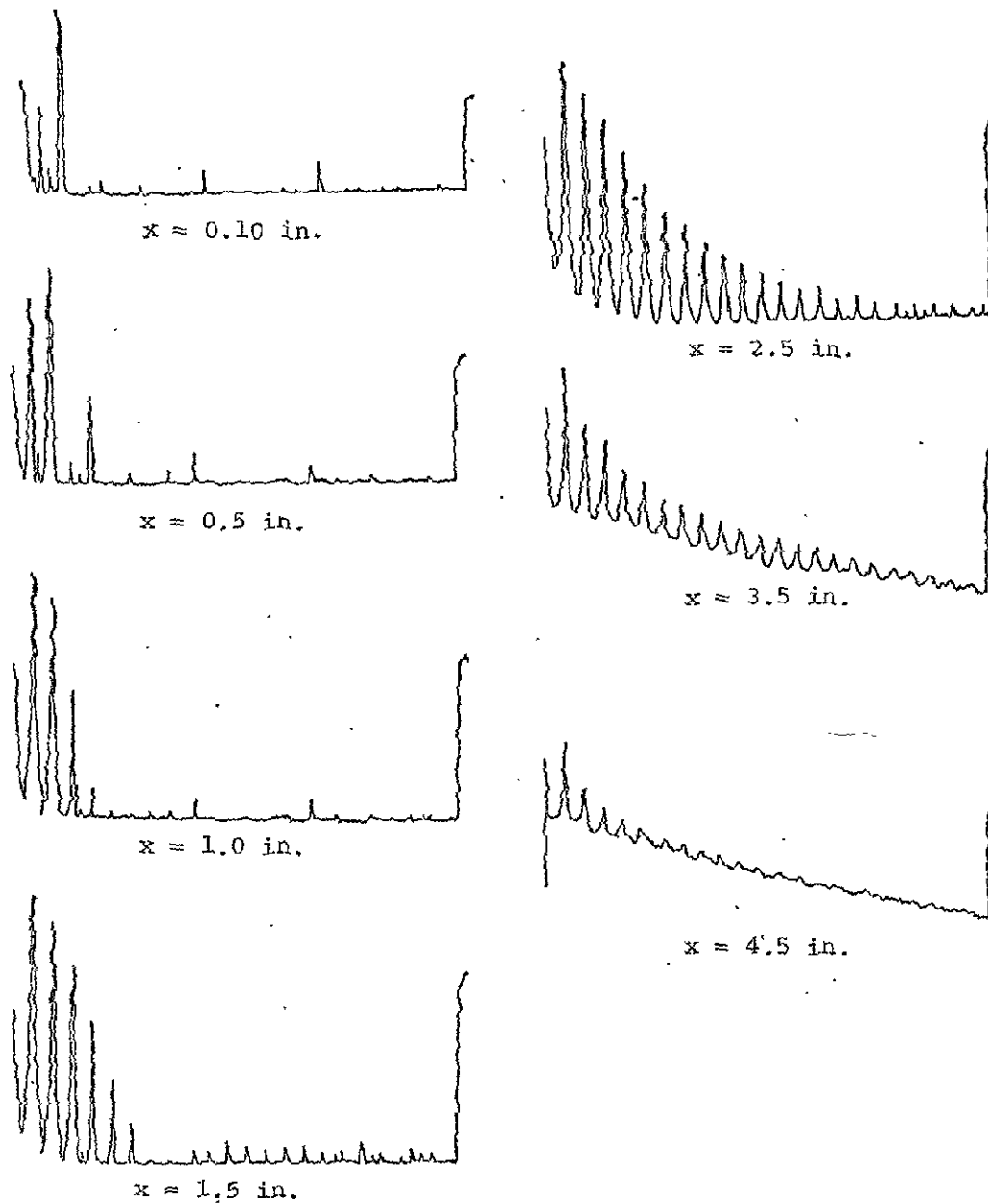


Figure 6 Streamwise evolution of the u-spectrum on the jet centerline.

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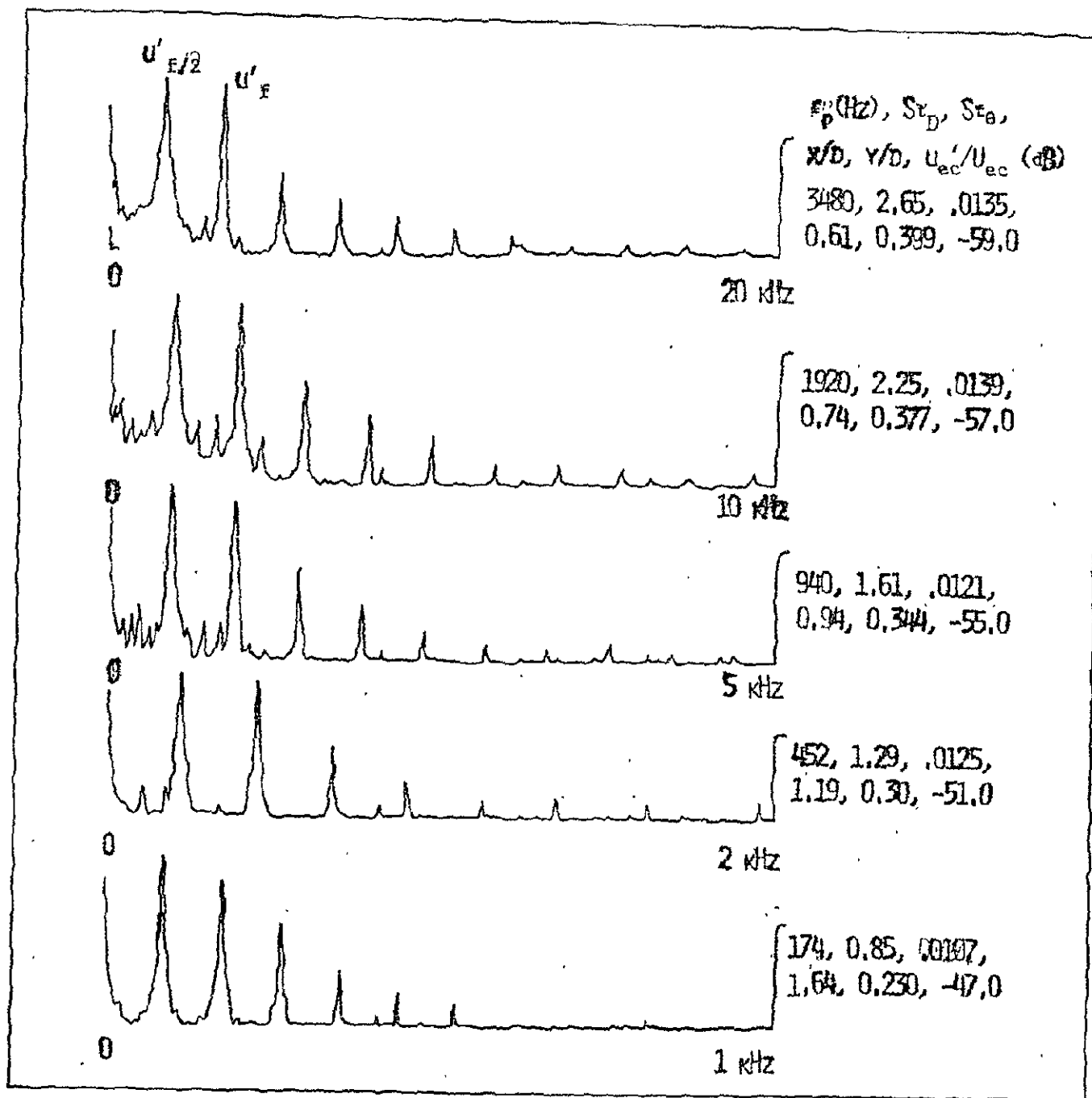


Figure 7

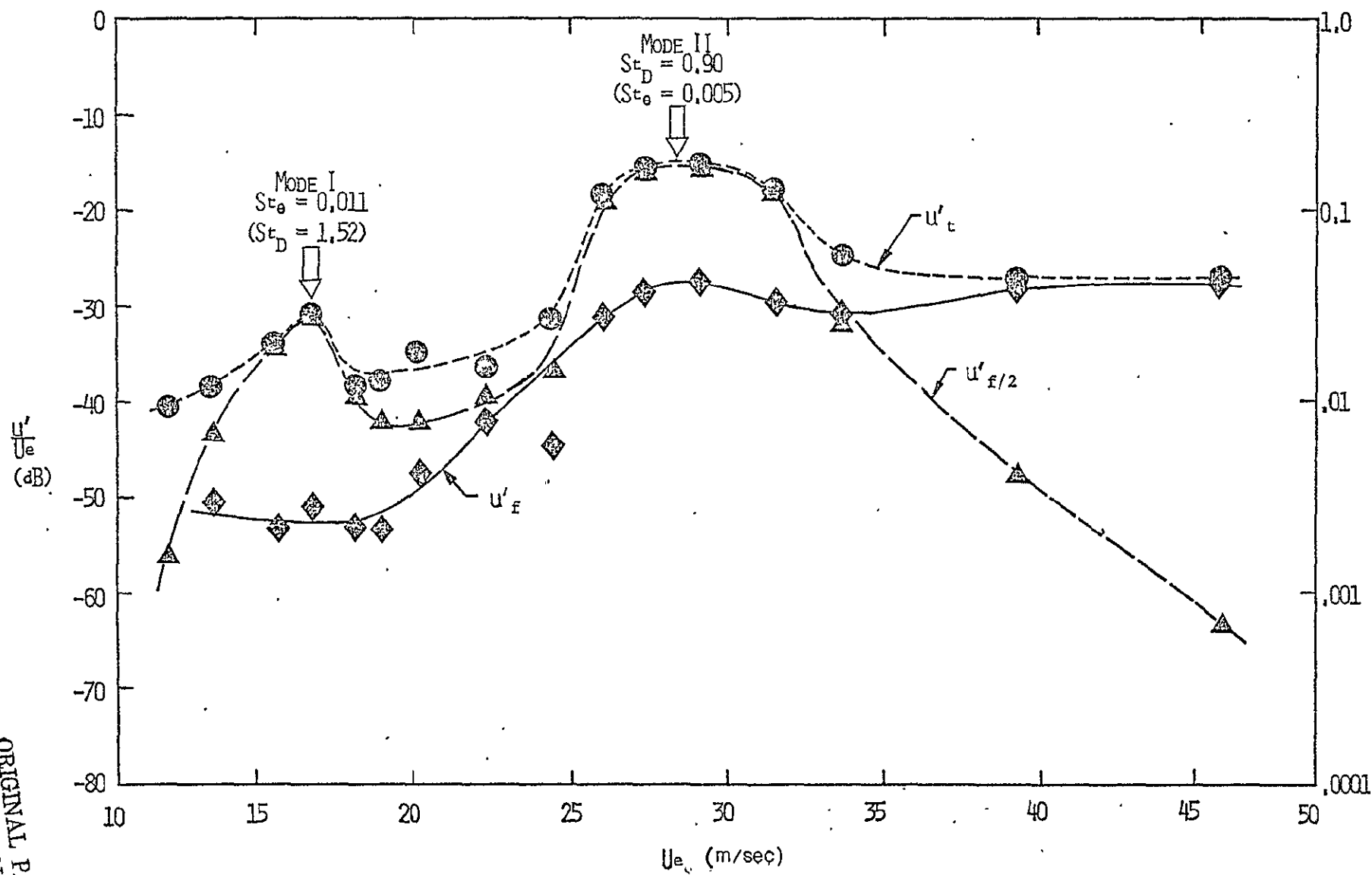


Figure 8a

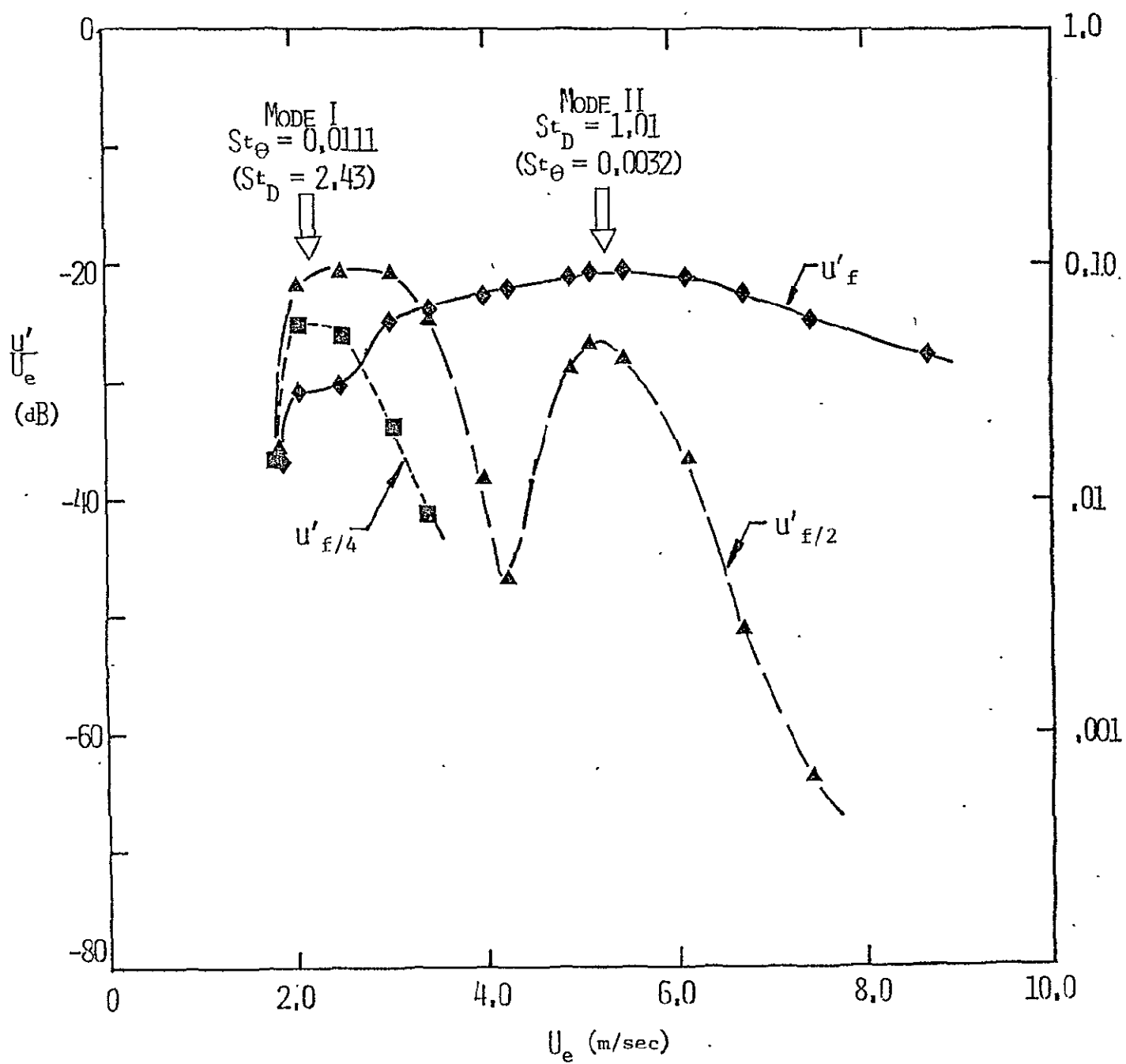


Figure 8b

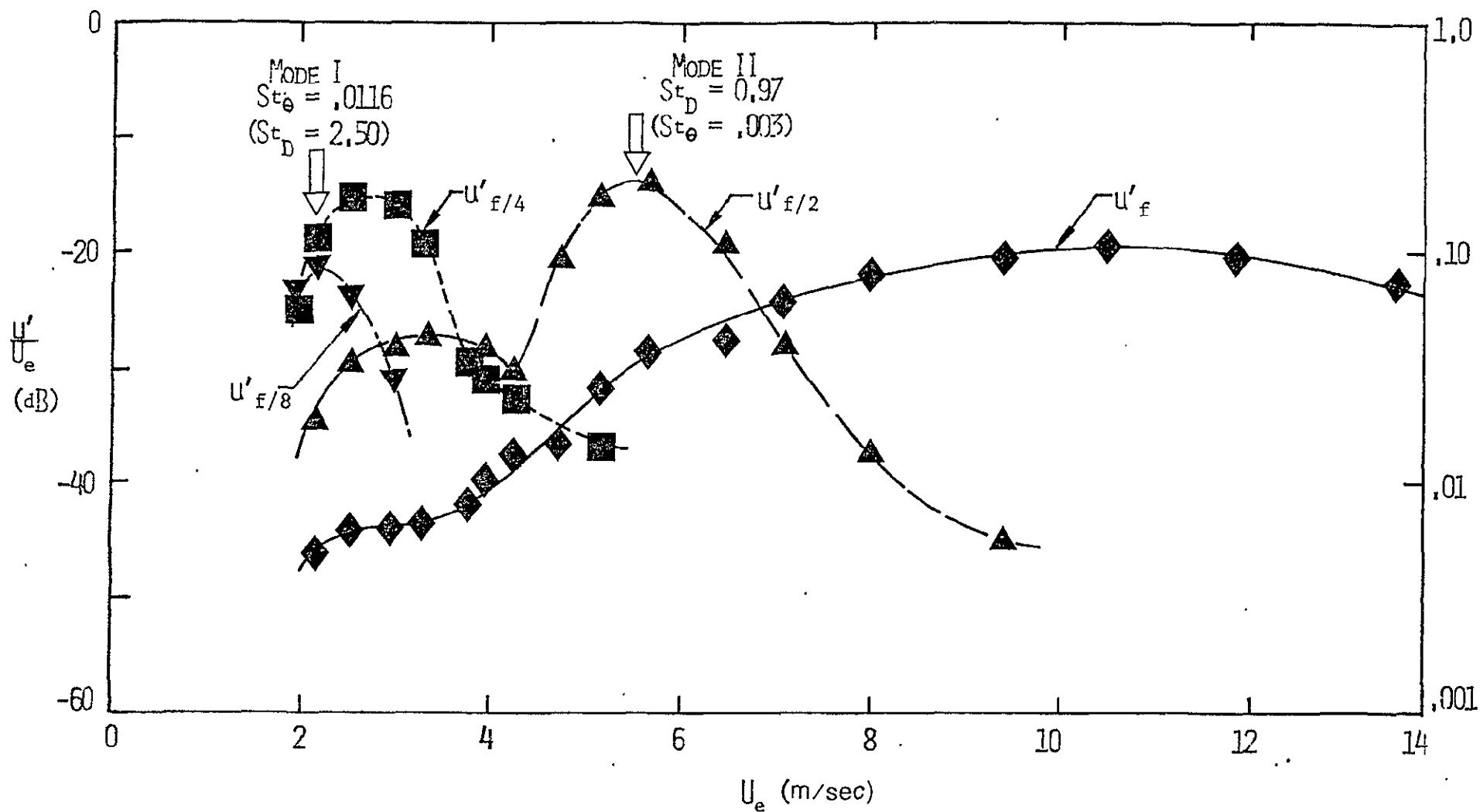


Figure 8c

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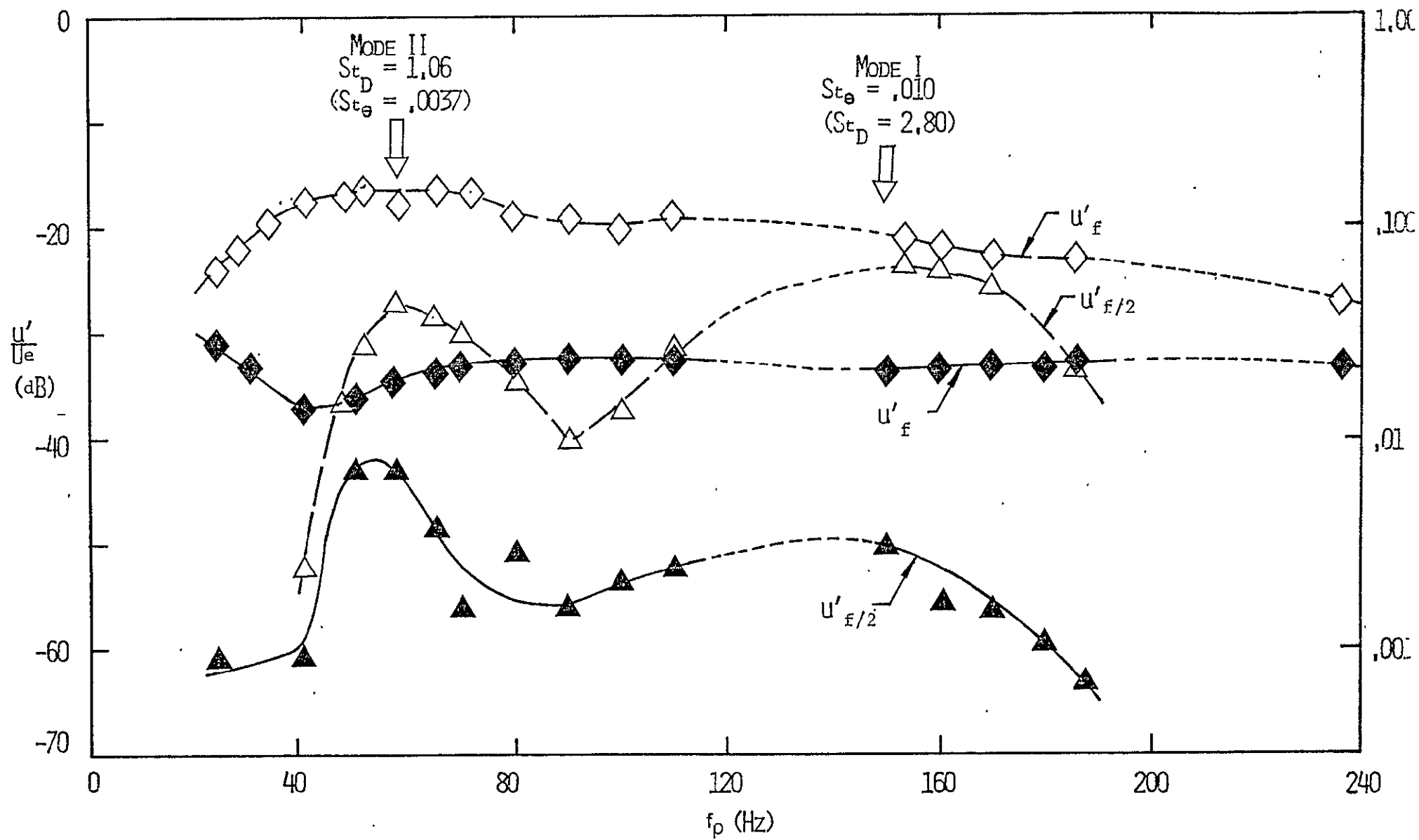


Figure 9

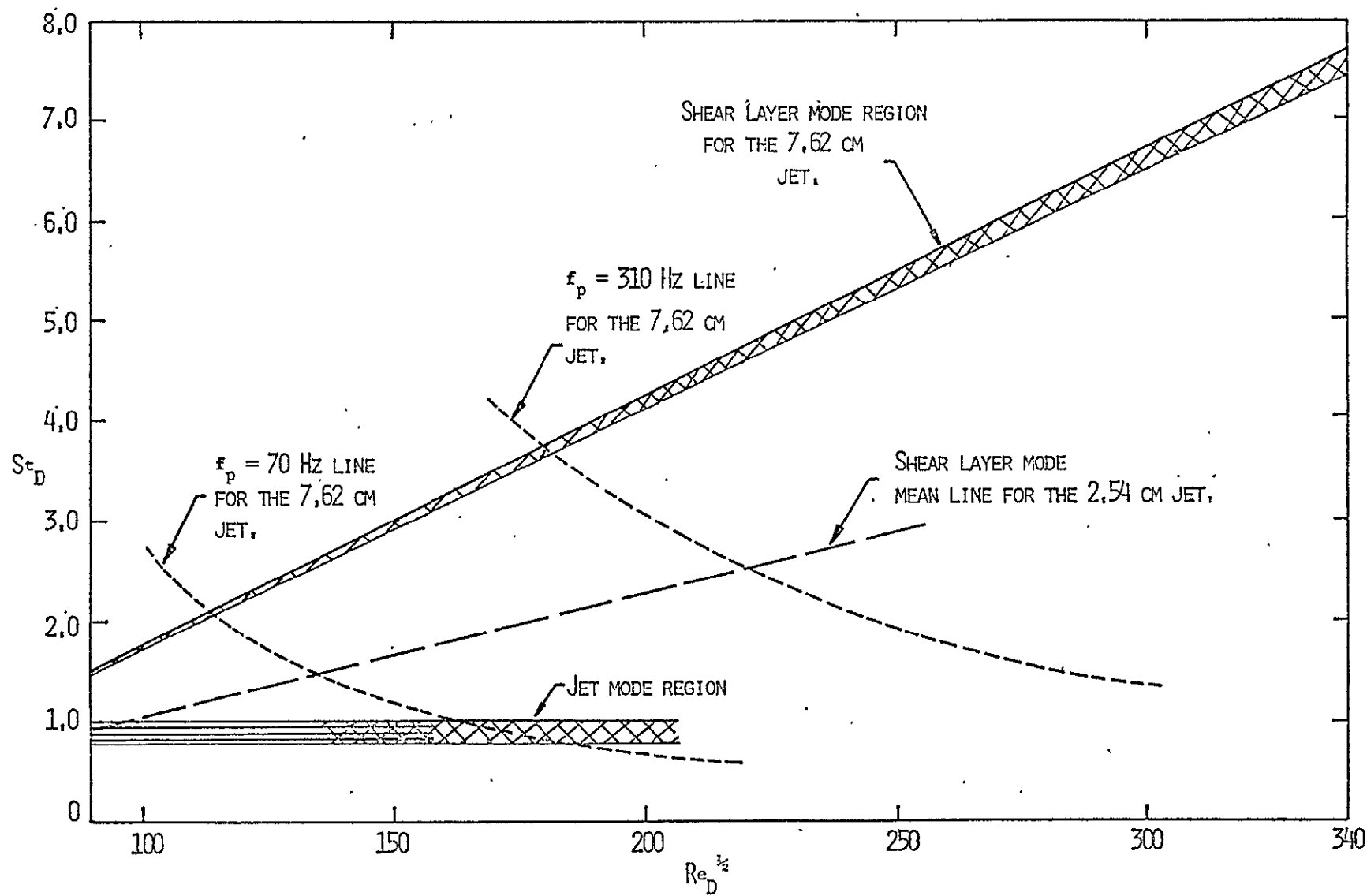


Figure 10

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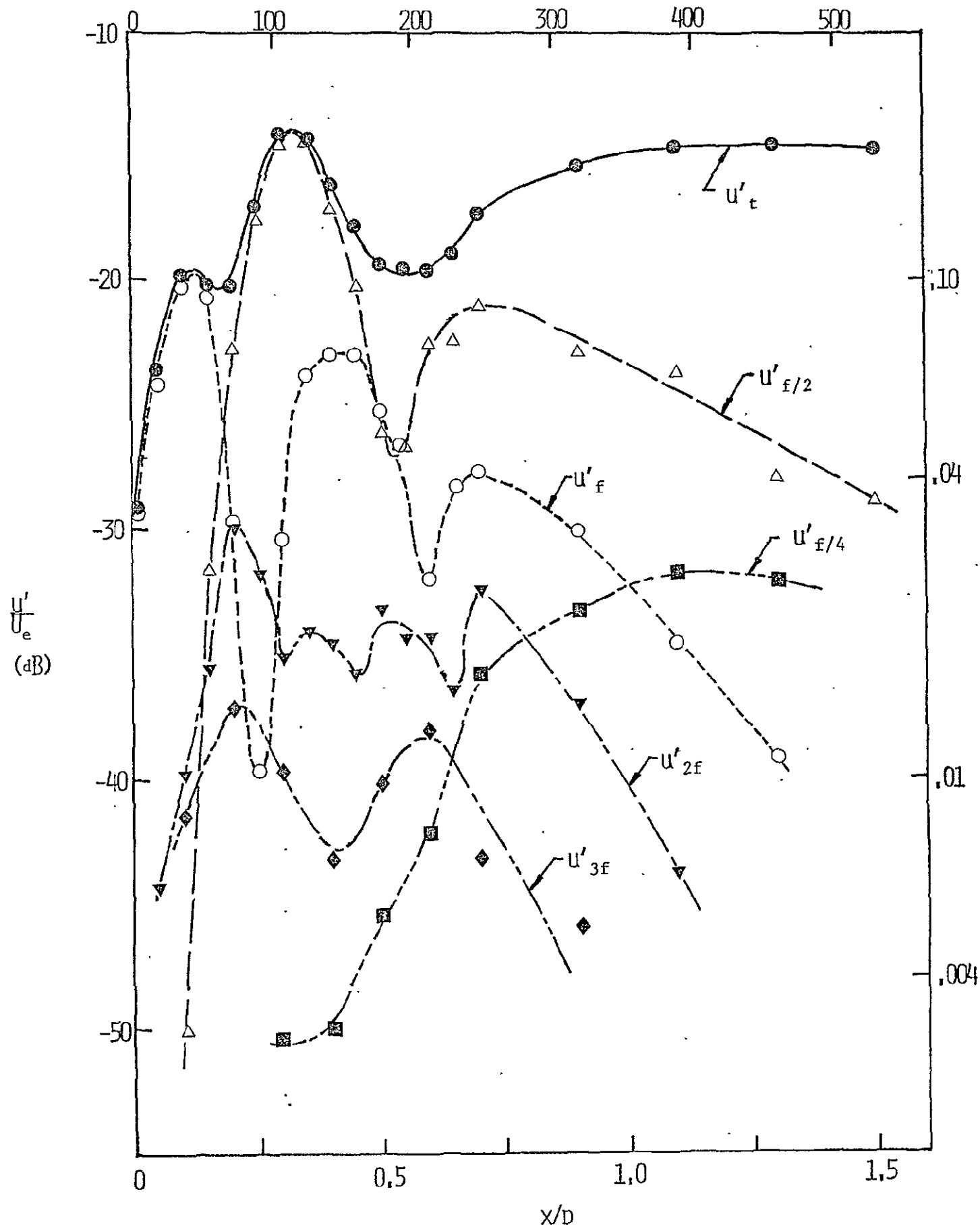


Figure 11

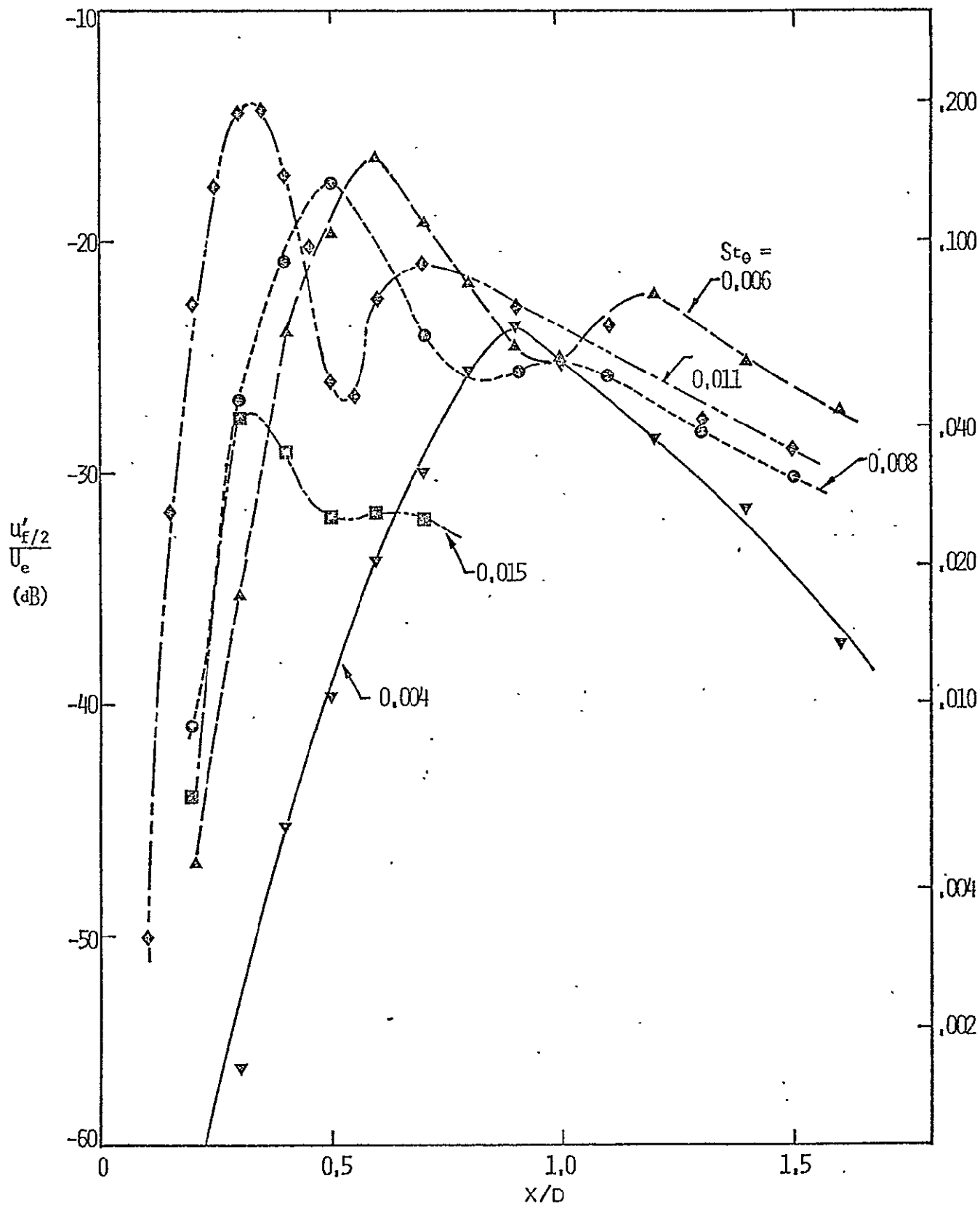


Figure 12

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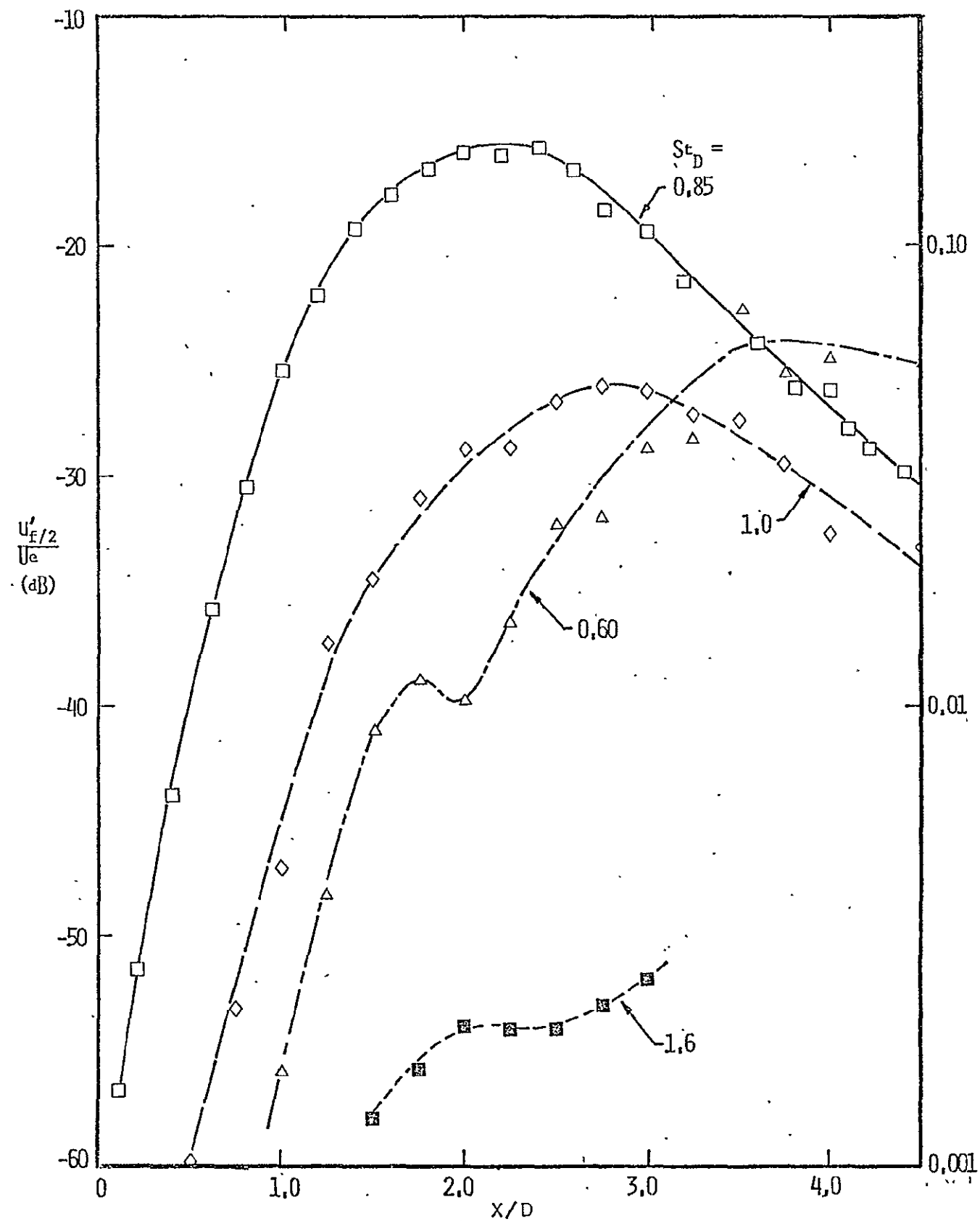


Figure 13

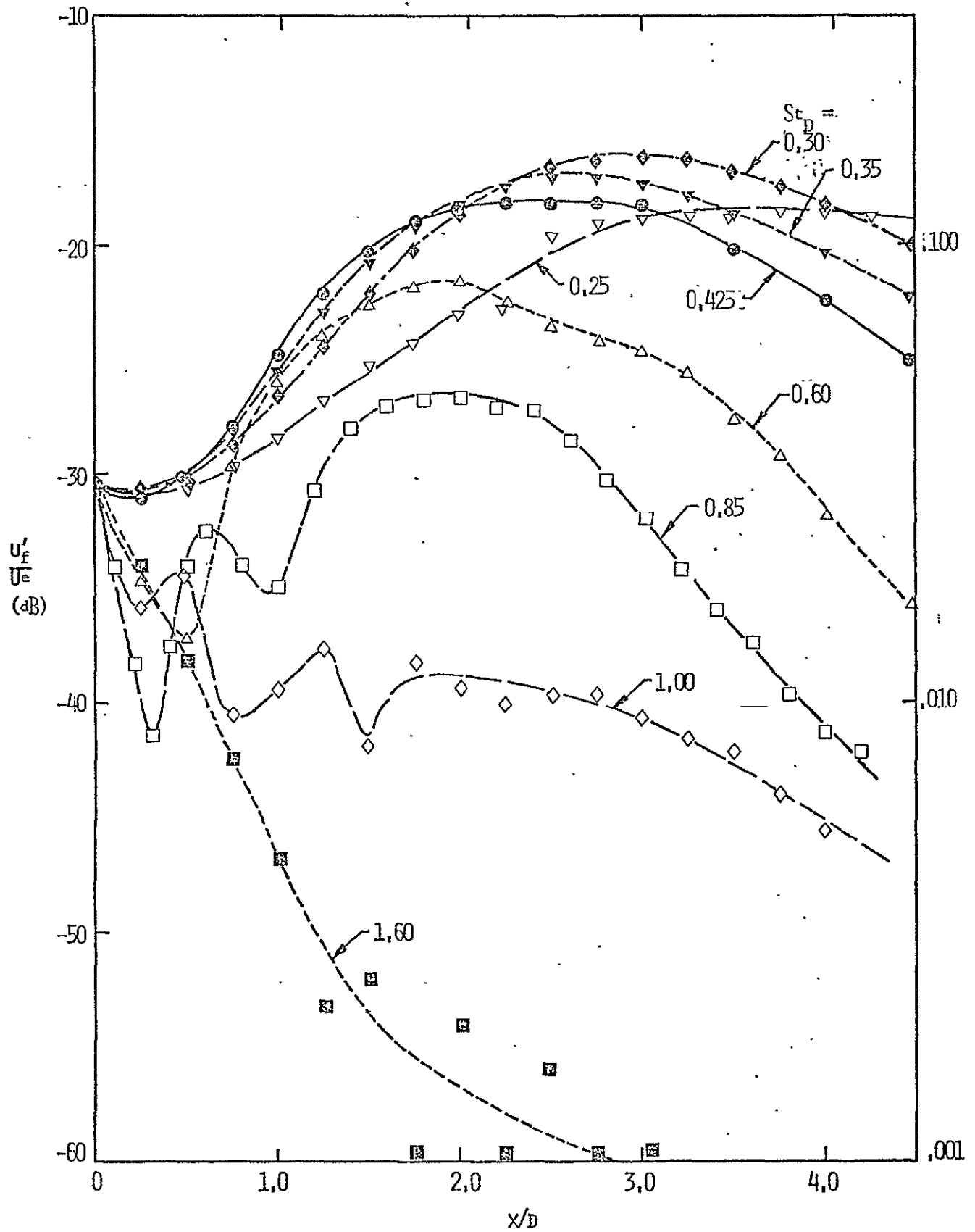


Figure 14

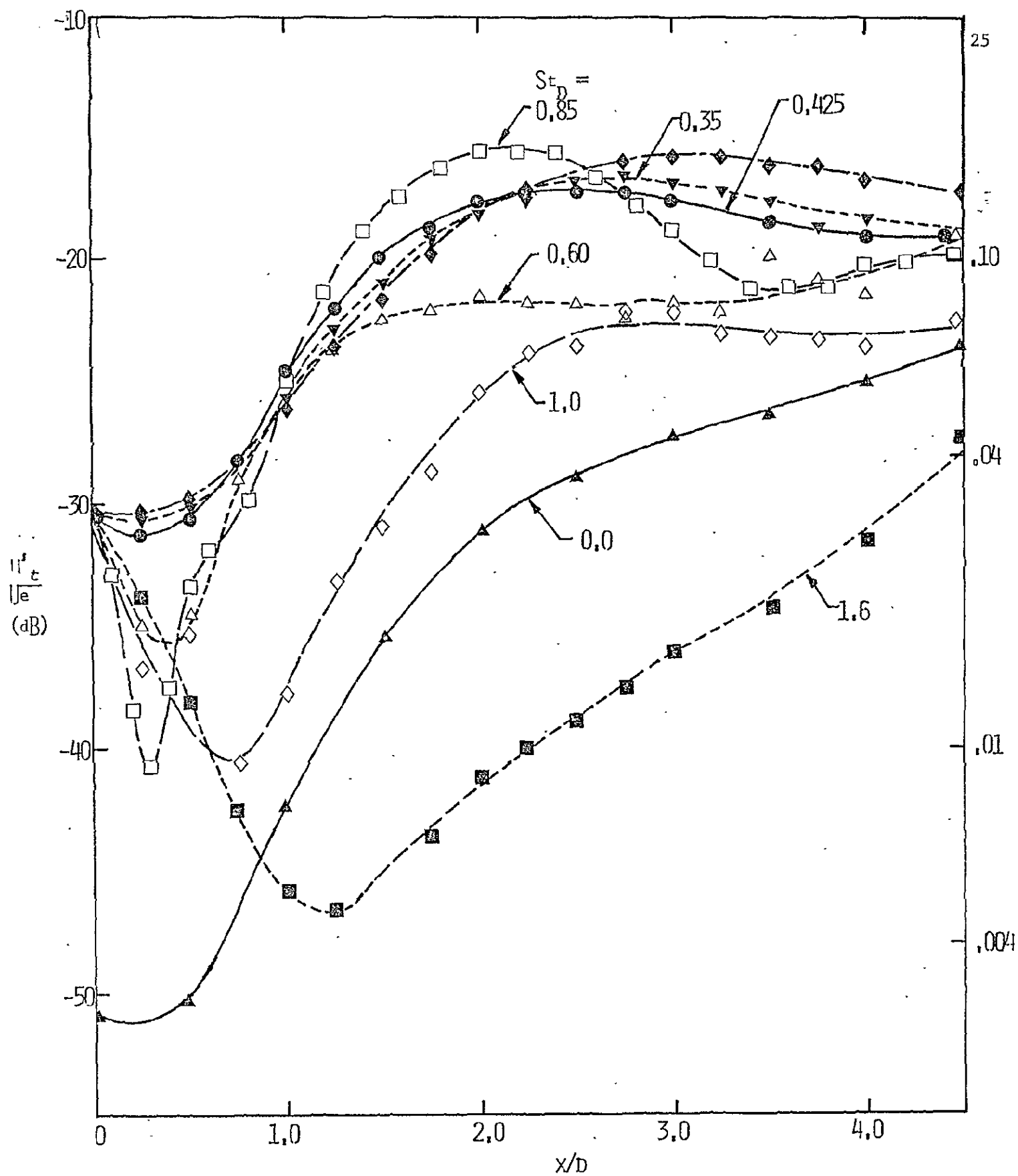


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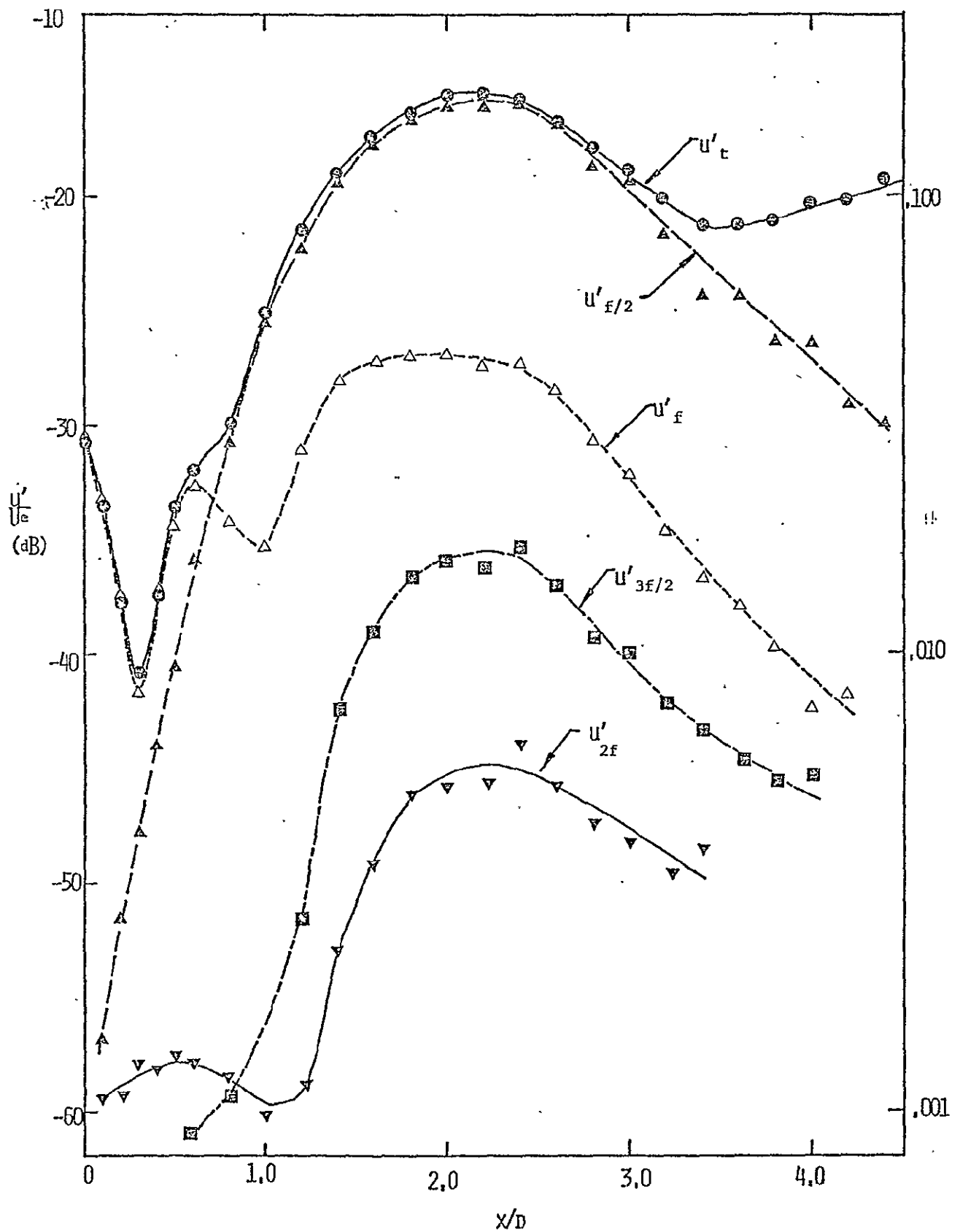


Figure 16

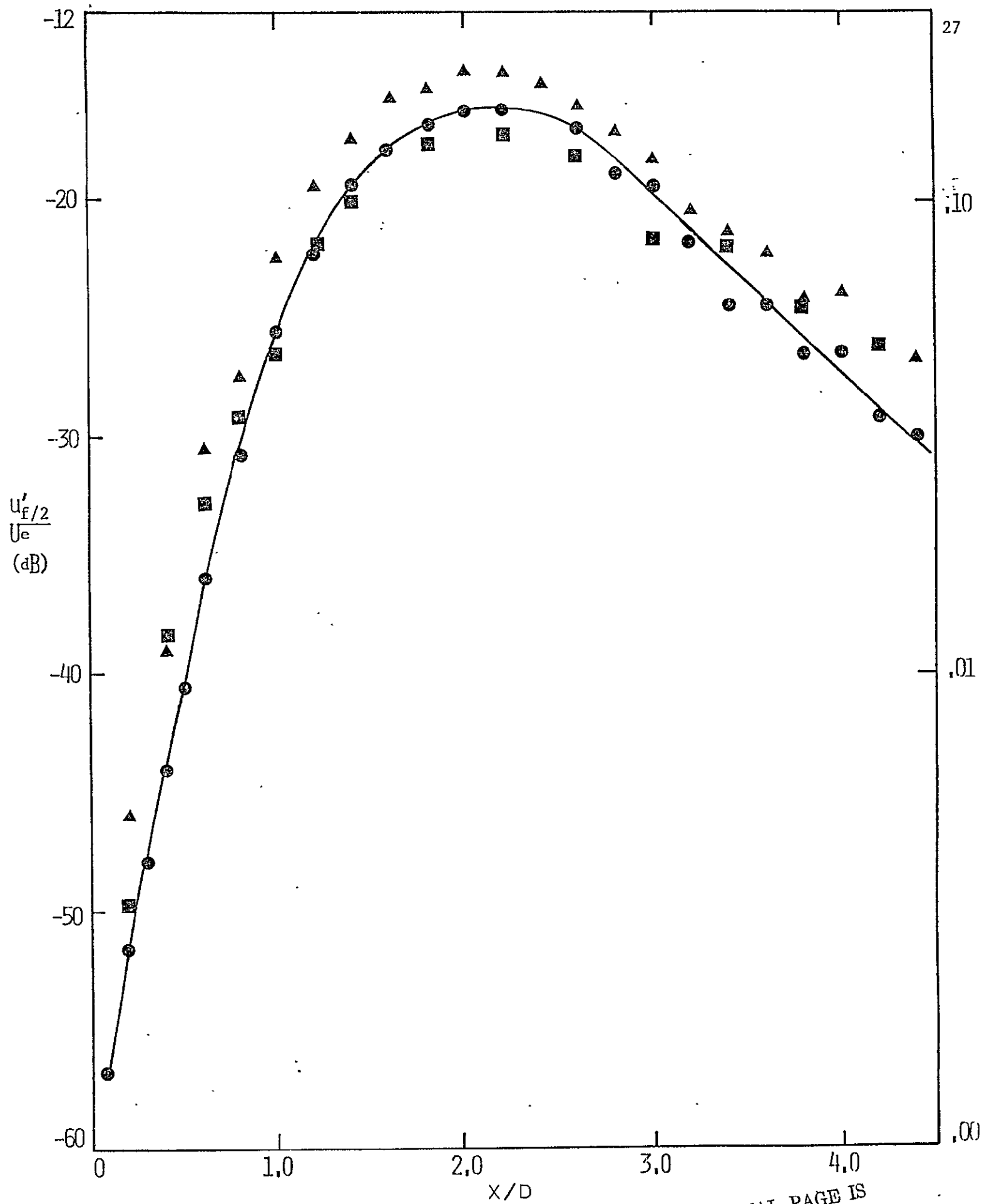


Figure 17

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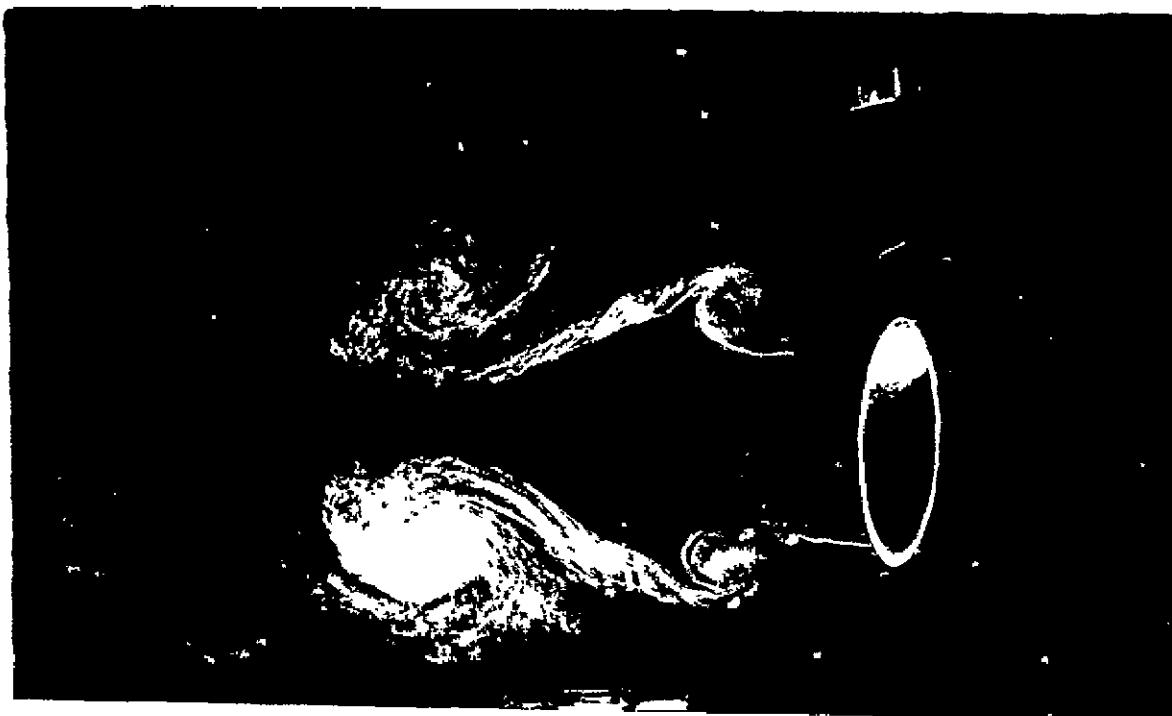


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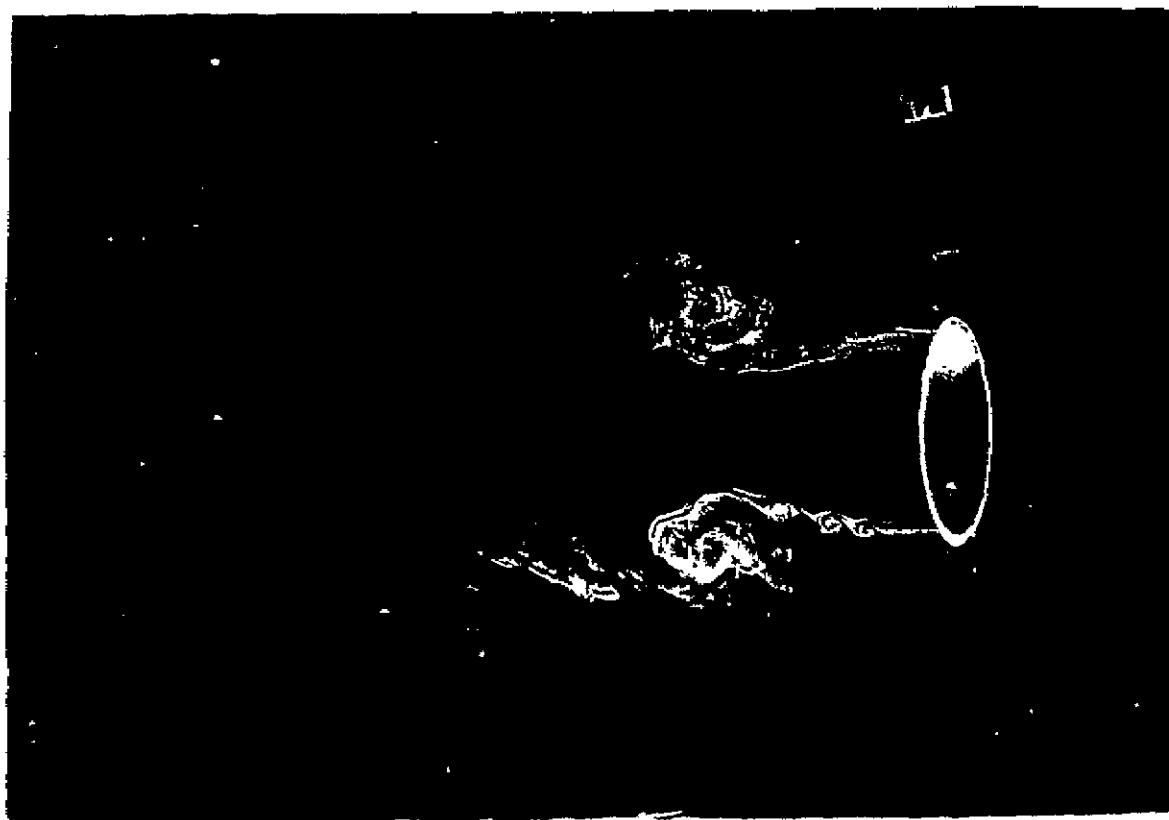
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Figure 18

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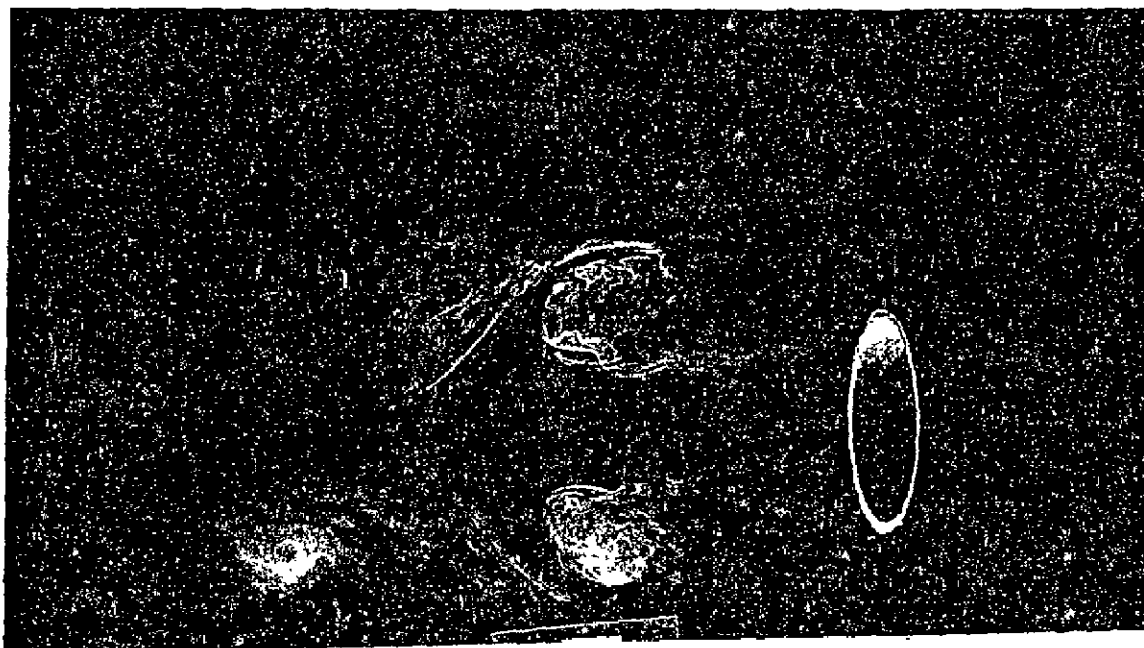
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Figure 19



(a)



(b)

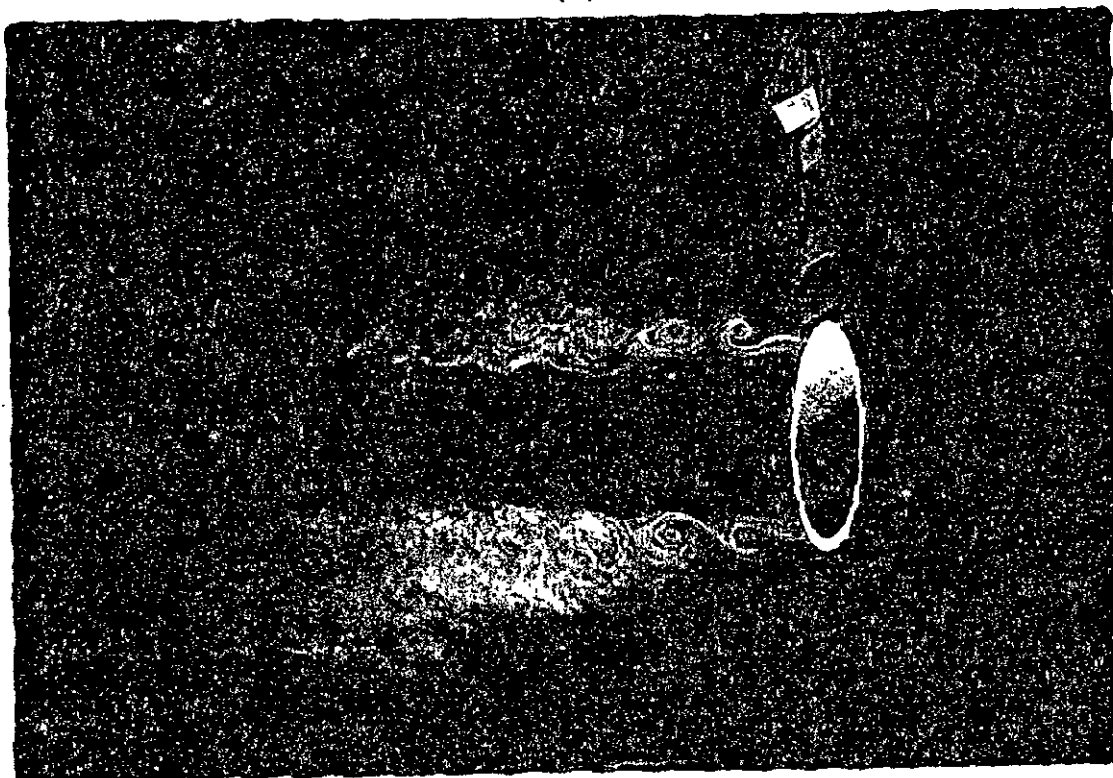
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Figure 20

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4.6

Figure 21

Chapter III

The Free Shear Layer Tone Phenomenon and
Probe Interference

Abstract

Free shear layer stability measurements with a hot-wire revealed that the probe itself can trigger and sustain upstream instability modes like the slit jet-wedge edgetones; this phenomenon is appropriately termed the free shear layer tone. The characteristics of the flow fields associated with the tones induced in incompressible axisymmetric and plane air free shear layers by a hot-wire probe and by a plane wedge were then explored experimentally over a range of Reynolds numbers and Strouhal numbers. These new data, while showing some similarity between the jet edgetone and the shear layer tone, affirm that the latter phenomenon is different in many ways from the widely investigated jet edgetone phenomenon.

As many as four frequency stages have been identified, there being a fifth stage associated with the subharmonic generated through vortex pairing in the free shear layer. No evidence of hysteresis could be found in the shear layer tone. In an overlap (i.e. interstage jump) region, the shear layer tone induced velocity amplitude variations with the lip-wedge distance h or the shear layer velocity scale U_e were independent of whether a given h or U_e was approached from a higher or a lower value. In the overlap (i.e. bimodal) regions, the shear layer tone occurred in one mode only at a time while intermittently switching from one mode to the other. Unlike the case in jet edgetone, the Strouhal numbers based on h , as well as on the free shear layer momentum and vorticity thicknesses increase with increasing stages of frequency jumps while the stage associated with the subharmonic obviously showed a drop. For the cases studied, it is shown that the frequency variations in each stage of the shear layer tone collapse on a single curve when nondimensionalized with the initial momentum thickness θ_e or with h , and

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plotted as a function of h/θ_e . These data also suggest that the shear layer tone phenomenon is also dependent on the initial condition of the free shear layer.

Phase average measurements locked onto the tone fundamental show that the shear layer tone phase velocity and wavelength are essentially independent of the stage of tone generation; in each stage, both phase velocity and wavelength decrease with increasing frequency but undergo jumps at starts of new stages. The measured shear tone induced fluctuating velocity fundamental amplitude and phase profiles across the free shear layer, as well as the variations of the shear tone wavenumber and phase velocity with the Strouhal number, show reasonable agreement with the predictions of the spatial stability theory. The data indicate that the feedback mechanism is hydrodynamic rather than acoustic. The shear layer tone wavelength λ bears a unique relation with h , this h - λ relation being different from the Brown-Curle equation for the jet edgetone.

The shear layer tones are unavoidable in near field shear layer measurements involving invasive probes, and can produce measurements which are not the characteristics of the free shear layer itself. A method for determining the true free shear layer natural instability frequency with a hot-wire is also presented.

I. MOTIVATION AND INTRODUCTION

1.1 Introduction: The developing region of free turbulent shear layers is dominated by large-scale organized structure which plays the key role in entrainment, mixing and noise production (Browand and Laufer 1975, Brown and Roshko 1974, Bishop et al. 1971, Liu 1974). Even in the self-preserving region where much of the turbulent kinetic energy has cascaded down - through nonlinear interactions - from these large scales to smaller scales, the large-scale organized structure is believed to play the major role in the transport of momentum, heat and mass. It is quite

likely that the organized structure of the developing region persists in the so-called self-preserving region of these shear flows. Characteristics of the organized structure and conditions favoring their formation and sustenance are of fundamental importance in free turbulent shear flows (Liepmann 1976, Roshko 1976).

Some recent studies (Bradshaw 1966, Hussain and Clark 1977, Hussain and Zedan 1977) show that the average measures of a free shear flow depend strongly on the initial condition viz., the characteristics of the initial boundary layers producing these flows. (Thus, it is likely that the large-scale organized structure in a turbulent free shear flow never achieves true self-preservation or local invariance in a finite flow length.) When the initial free shear layer is laminar, the wavelength of its most unstable mode, which depends on the velocity distribution, identifies the initial spacing of the rolled up vortices and thus the initial large-scale size. However, these vortices may undergo interactions like coalescence (or tearing) producing progressively larger and larger scales of coherent motions (Brown and Roshko 1974, Winant and Browand 1974, Zaman and Hussain 1977, Moore and Saffman 1975). When the initial boundary layer is turbulent, its various integral measures like momentum thickness and shape factor, and turbulence characteristics like intensity, probability density, Reynolds stress and spectra, may be taken as the identifiers of its initial condition. It is also possible that an initially turbulent free shear layer can roll up into organized large-scale vortical motions which then evolve not unlike the initially laminar case.

Very little is known about the effect of the initial condition on the development of free turbulent shear flows (Kline et al. 1973, Bradshaw 1966, Hussain and Clark 1977, Hussain and Zedan 1977) or about the effect of controlled periodic excitation on the near-field large-scale coherent structure of free shear flows

(Crow and Champagne 1971, Hussain and Thompson 1975). This paper is an offshoot of our continuing investigation obtaining basic information in this area.

While flow visualization can be highly effective in qualitatively understanding the large-scale coherent structures and their kinematics, hot-wire is the commonly employed tool for acquiring quantitative and accurate aerodynamic data. (The laser-Doppler velocimeter has its unique limitations and is still rather expensive, being used largely in special situations only). During hot-wire measurements of the natural roll-up frequencies of initially laminar free shear layers, in connection with our study of controlled excitation of free jets (Hussain and Zaman 1975), we found that the measured roll-up frequency was a function of the streamwise distance of the hot-wire from the lip i.e. the separation point. As the probe was traversed in the streamwise direction within the free shear layer the frequency progressively decreased, followed by jumps at intervals to higher values. Especially the latter feature, affirmed by repeated measurements, appeared inexplicable on the basis of any plausible shear layer dynamics. Other authors have observed frequency dependence on x but attributed it to the Doppler effect or refraction effect of sound waves in the noise producing region (Winant and Browand 1974, Ko and Davies 1971, Ko and Kwan 1976). Neither of these effects could explain the apparent peculiarity of our data. Recognizing that the streamwise variations of the shear layer instability frequency observed by us were similar to those occurring in the jet-wedge edgetone phenomenon, we were then able to establish that the apparent peculiarity of our data was due to the edgetone effect of the hot-wire probe on the free shear layer.

1.2 The Edgetone Phenomenon: When a thin slit jet impinges symmetrically on a plane wedge the resulting sound is called jet edgetone. The sound has interesting characteristics: the sound frequency spectrum has a strong peak; the peak

frequency increases with decreasing jet-wedge distance h or with increasing jet speed U_e followed by positive jumps, the regions between jumps being called 'stages'; there is a minimum value of h below which no edgetone occurs; for a fixed jet-wedge distance there is a minimum speed below which no edgetone occurs also; the inter-stage frequency jumps are associated with hysteresis i.e., the jump frequencies depend on whether h or U_e is increased or decreased; etc.

The jet edgetone phenomenon was first reported by Sondhaus in 1854. Helmholtz, and Rayleigh, among others, also studied it, but it was Waschmuth who in 1904 first looked at edgetone in the absence of a resonator. His interpretation was that the jet acted as a flexible rod pendulating on impact on the wedge and that the noise radiated from the wedge rather than the jet, probably due to vibration of the wedge. Benton in 1912 demonstrated that wedge vibration was not necessary for edgetone production. Schmidtke in 1919 postulated the presence of Karman vortex streets along the sides of a wedge in Stage I and between the jet and wedge in higher stages. Kruger was the first who, in 1920, tried to explain the frequency jump to be the consequence of the condition that the jet-wedge distance h be a multiple of the most unstable mode wavelength λ of the jet. He also suggested that a compression wave travels back to the jet exit to maintain a self-sustained edgetone; this acoustic feedback concept was presumably shown to be erroneous by Richardson (1931), who also inferred from his data that $h/\lambda = \text{stage of the edgetone}$. Brown (1937a) made careful smoke visualization to provide probably the most comprehensive documentation yet of the jet edgetone flow, and derived the empirical formula for the edgetone frequency f ,

$$f = 0.466j(U_e - 40) \left(\frac{1}{h} - .07 \right), \quad (1)$$

where $j = 1, 2.3, 3.8, 5.4$ in stages 1, 2, 3 and 4; U_e is the exit velocity and h

the jet-wedge distance. Brown concluded that the stage I can occur simultaneously with any of the other stages. In his second paper, Brown (1937b) emphasized the superficiality of the existing interpretations of the edgetone mechanism and argued that at low speeds the jet disturbance caused by the wedge was the controlling factor while at high speeds acoustic feedback from the wedge produced the edgetone.

Curle (1953) extended Kruger's and Richardson's ideas by postulating that the instability of the jet produces its pendulation which in turn triggers separation vortices alternately on the two sides of the wedge. The circulation associated with these vortices induces coherent embryonic vortex formation back at the jet exit; these vortices then grow due to jet instability, thus providing the stable feedback. He rejected the role of fluid compressibility, and based on Brown's (1937a) data he argued that the $h-\lambda$ relation for the hydrodynamic phenomenon should be

$$h = (J + \frac{1}{4})\lambda, \quad (2)$$

where the integer J is the stage of edgetone.

Nyborg (1954) developed a dynamical theory by assuming that the jet consisted of a streak of discrete particles under the action of uniformly distributed transverse force field. The central hypothesis is that the transverse acceleration of each particle depends only on its distance from the jet exit and its instantaneous transverse displacement. The resulting integral equation for the jet displacement, even for simple choices of trial functions for the integrand, produced self-sustained oscillation solutions with realistic frequency variations and jet trajectories. This simplistic theory, however, fails to predict when the frequency jumps will occur, and why there should be a lower limit of h for the existence of edgetone.

Powell (1961) considered the edgetone phenomenon to consist of four simultaneous effects, the net transfer function for the stable feedback system being the product

of the effectiveness of each. Each effect is represented as a complex gain factor having an amplitude and a phase change; for the case of stable self-excitation the total gain must be unity and the total phase change an integral multiple of 2π . Recognizing the complexity of the jet flow field, Powell used the Brown-Curle relation (2) as an independent criterion to account for the flow field's part in the feedback control loop. He then developed a nonlinear gain criterion to explain the existence of the lower limit of the jet-wedge distance for edgetone production. This theory also explained multiple tones, frequency jumps and frequency hysteresis.

Curle's hydrodynamic theory assumes that the vortex generated on each side of the wedge by the jet triggers instantaneously an embryonic vortex at the lip on the same side but of opposite sign. Nyborg's theory, however, is totally devoid of the flow physics and its limited success would appear to be fortuitous. Powell's theory differs from Curle's in that the feedback in the former is acoustic while it is hydrodynamic in the latter. Powell's theory has been regarded as probably the most rigorous. However, the $n + \frac{1}{4}$ wavelength criterion used by Powell is arbitrary. The cornerstone of Powell's theory is the nonlinearity of jet disturbance while it can be argued that at least for the first stage the nonlinearity may not be large. In spite of the efforts by these leading researchers, the jet edgetone theory is still unsatisfactory, indicating incomplete understanding of the phenomenon.

Woolley and Karamcheti (1974) have attempted to show through their quasi-parallel flow instability computations that the nonparallel nature of jet flow can explain most edgetone characteristics.

1.3 Motivation and Objective: While investigating the free shear layers of plane and circular jets near their exits with the help of hot-wires, we discovered that a single free shear layer can also produce large-amplitude, sustained oscillations

like those in a jet edgetone. Literature failed to reveal any previous study of the free shear layer tone phenomenon. The instability characteristics of these shear layers (Michalke 1965, 1972; Freymuth 1966, Hussain and Thompson 1975) associated with a top-hat velocity profile at the jet exit are different from those of the slit jets with parabolic exit profiles (Sato 1960) used in conventional edgetone studies (Karamcheti et al. 1969). In the jet-wedge edgetone, the jet impinges on the wedge symmetrically; there is lack of such symmetry in the shear layer tone. While Curle's (1953) hydrodynamic theory is based on the symmetric vortex patterns of opposite signs on the two sides of a jet which trigger vortices of opposite sign on the two sides of a wedge, the rolled-up vortices in a mixing layer are of one sign only. This suggested that the edgetone characteristics in a single free shear layer would be different from those in a slit jet; hence the motivation for this study. As we will see, the shear layer tone has some similarities with the jet edgetone as well as some differences. Our detailed hot-wire measurements in the shear layer not only document this phenomenon but also shed further light on the jet edgetone phenomenon itself.

There are numerous practical applications where the shear layer tone is of interest: these range from whistles, to holes in transonic tunnel walls, to cavities in various kinds of wind tunnels, in rocket motors and in continuous lasers to open cavities on flight vehicles, ships and submarines. In some of these, the shear layer tone phenomenon can produce excessive noise or structural vibrations or heat transfer or drag. In the presence of a cavity the shear layer tone is coupled with the cavity resonance; the free shear layer tone is not influenced by any such cavity resonance. To our knowledge, this is the first study of a free shear layer tone.

After the completion of this work, the authors became aware of two independent, contemporary investigations (Bolton 1976, Sarohia 1976) of oscillation in flows

over cavities. Bolton (1976) has studied the excitation of a Helmholtz resonator jacket covering a circular orifice (cutout) in a turbulent pipe flow, the turbulent free shear layer in the gap providing the excitation to the resonator. Hot-wire measurements were carried out in the pipe downstream from the gap but not in the turbulent shear layer in the gap. He concluded that the feedback phenomenon is hydrodynamic.

Sarohia (1976) has studied oscillation of laminar flows over cavities on slender axisymmetric bodies. Even though his study shows that the data are independent of cavity depth below a certain size, the acoustic modes and hydrodynamics in the cavity obviously play a significant role. Furthermore, his study is inherently different from ours, the former being influenced by multiple length scales associated with the slotted slender body. In spite of the configuration differences, the hot-wire based data of Sarohia provide some details of the local shear layer oscillations; these data will be compared with ours whenever appropriate.

II. EXPERIMENTAL APPARATUSES AND PROCEDURES

The experiments were carried out in the free shear layers of a plane and a circular air jet facilities; for brief descriptions of the two facilities see Hussain and Clark (1977) and Hussain and Zaman (1975), respectively. A 2.54cm diameter nozzle follows the 25.4cm diameter settling chamber in the circular jet facility; the 140 cm x 3.18 cm plane jet follows the 140 cm x 140 cm settling chamber. Both flows exit through perpendicular end plates and discharge in a large laboratory with controlled temperature, humidity and traffic. Data were obtained by standard hot-wire techniques employing constant temperature (DISA) anemometers and a 0.2cm-long tungsten hot-wire of 4μ diameter.

The hot-wire probe traverse in streamwise (x), traverse (y), and vertical (z) directions and rotation (α) in the horizontal plane were carried out by remote

control through the action of stepping motors with resolutions of 0.00254 cm and 0.01 degree, respectively. While these traverses of the hot-wire for most of the data were done through remote manual control, integral measures of the profiles were obtained on-line with our laboratory minicomputer (HP 2100).

A Spectroscope SD335 spectrum analyser (with a maximum range of 0-50 kHz in 500 frequency lines) was used to obtain the spectra of the velocity signals. Unless otherwise stated, an ensemble average of 128 successive realizations was obtained for each velocity spectrum; the amplitudes and frequencies of the spectral components reported were read directly from the spectrum analyzer.

A PAR 129A lock-in-amplifier was used to carry out phase averages from which rms amplitudes and phase variations of the shear layer tone induced velocity fundamental as well as the disturbance wavelength and phase velocity were determined. In the tones produced by a sharp wedge, the phase measurements were carried out with the help of two hot-wire probes. Both the probes were placed on the outer skirt (i.e. the zero velocity side) of the shear layer, their stems making large angles α with the flow direction so that the probes themselves were not involved in producing any significant effect on the shear layer tone flow. One probe was kept fixed and its narrow bandpassed signal was used as the reference signal for the lock-in-amplifier, which gave the phase difference of the signal from the second probe at any point in the flow with respect to the reference signal.

For all measurements reported in this paper, the initial boundary layer was laminar. The boundary layer at 0.3 cm before the lip (i.e. the separation point) was carefully traversed with the hot-wire to record mean velocity and longitudinal fluctuation intensity profiles. The velocity fluctuations in this boundary layer were observed to be of fairly low frequency both by scope trace check and by spectral analysis; these can be traced to either settling chamber cavity resonance

frequencies or blower blade frequency. The fluctuation intensity profile was consistent with that of a time-dependent laminar boundary layer (Hussain and Clark 1977). The mean velocity profile shape factor was very close to the flat plate laminar boundary layer (Blasius profile) value of 2.59. Considering all these factors, we considered the initial condition to be laminar.

Figure 1(a) shows the schematic of the flow and the probe orientation in the flow; the detailed geometry of the hot-wire probe used is shown in figure 1(b). A 1.27cm wide and 3.81cm long, 20-degree sharp wedge (figure 1(c)) was used to study the basic physics of the free shear layer tone.

Unless otherwise stated, all single probe data were taken with the probe (acting as the wedge) inclined at an angle α of about 20-degrees with the x-axis (figure 1(a)). Most of the data reported here pertain to the plane free shear layer of a plane jet with top-hat velocity profile, within one gap-width downstream. Note that the jet exit center has been conveniently chosen as the origin of the coordinates. Also note that while the streamwise distance of the velocity measurement point is denoted by x , the distance of the wedge-tip from the exit plane (lip) is denoted by h . Spectrum data presented refer to one-dimensional longitudinal velocity frequency spectrum, $S_u(f)$, defined such that $\int_0^\infty S_u^2(f) df = \overline{u^2}$.

III. RESULTS AND DISCUSSION

3.1 Free shear layer tone induced by a hot-wire probe

In this section we will concentrate on the nature of the probe induced shear layer tone.

3.1.1 Frequency variation with the lip-probe distance: Figure 2 shows the one-dimensional frequency spectra of the longitudinal velocity fluctuation u determined by the hot-wire probe placed at different axial locations x in the plane free shear layer. Only the single-wire probe as sketched in figure 1(b) was in the

flow at the y -location where $U/U_e = 0.95$, with the probe stem making an angle $\alpha = 20$ -degree with the mean velocity direction. The abscissa in these linear-linear spectra plots range 0-5 kHz; the ordinates of these figures were adjusted to highlight the spectral peaks. Figures 2(vi)-(xxiii) have the identical vertical scale; with respect to this scale, ordinates for figures 2(i)-(iii) are magnified by a factor of 10 and for figures 2(iv) and 2(v) by $(10)^{1/2}$. The frequencies of the spectral peaks indicated in these figures were read directly from the spectrum analyzer with a resolution of $\pm 0.1\%$ fullscale.

As can be seen in figure 2, the frequency of the spectral peak decreases as the probe is moved downstream from the lip. It should be mentioned here that similar spike in the spectra is observed upstream as near to the jet exit as $x = 0.33$ cm; the rms amplitude of this peak further upstream becomes too small to be distinguished from the background turbulence. This observation of monotonically decreasing spectral component amplitude with decreasing x apparently contrasts the existence of the minimum jet-wedge distance h_{min} observed for jet-wedge edgetone and will be discussed in greater detail in a later section.

With increasing hot-wire distance x from the lip, the frequency decreases; the rms amplitude increases and reaches a maximum at $x \approx 0.94$ cm before decreasing with increasing x . At $x \approx 0.94$ cm another peak at a higher frequency (i.e. stage II) shows up in the frequency spectrum. With increasing x , amplitude of this second mode continues to grow while that of the first one decreases, the frequencies of both, of course, decreasing progressively. At $x \approx 1.14$ cm the second spectral component reaches its peak amplitude and the first one has almost disappeared. As the probe is moved further downstream, the decay also of the second mode continues until at $x \approx 1.55$ cm when yet another mode (stage III) appears at $f = 3800$ Hz. Meanwhile a subharmonic component appears also. With further increase

in x this subharmonic rms amplitude steadily grows, and overtakes the fundamental in amplitude at $x \approx 2.46$ cm. The subharmonic component in the frequency spectrum marks the occurrence of coalescence among the rolled-up vortices in the free shear layer (see later).

The peaks in the velocity spectrum gradually disappear further downstream; the energy becomes distributed in frequency with gradual roll-off at higher frequencies, indicating progressive spectral broadening and randomization of flow fluctuations due to the evolving turbulence through the (nonlinear) cascade process.

The variation of the frequency of the spectral peak in the transverse direction was checked for a number of x-stations by traversing the hot-wire across the free shear layer. It was found that the spectral peak frequency remained essentially unchanged across the shear layer. Figure 3 shows one such set of data at $x = 0.94$ cm for the same plane free shear layer flow condition as used for figure 2. The abscissa of these linear-linear spectra plots range 0-5 kHz and the ordinates are arbitrarily chosen to accentuate the spectral peaks. The rms amplitudes of the spectral peaks are shown in dB with respect to 1.0V; (the mean voltage corresponding to U_e was 7.4V). Constancy of the spectral peak frequency in the transverse direction rendered subsequent measurements easier because the transverse position of the probe or the wedge in the shear layer was not critical as far as frequency measurement was concerned.

Figure 3 is also consistent with edgetone theories such as Curle's (1953), which state that the wavelength is determined by the lip-wedge distance. In fact, the slight decrease in frequency, around 1%, on either edge (side) of the shear layer is in agreement with the theory. The hemispherical leading end of the probe support acting as the wedge (discussed later) in this case was approximately 2.2cm downstream from the lip. A transverse traverse by 0.67cm increases the lip-wedge distance by about 1% which should increase the wavelength by the similar ratio, and thus produce a 1% decrease in the measured tone frequency. Further away on either side of the shear layer, the spectral peak decays due to decreasing tone induced velocity fluctuation amplitude, indicating that the shear layer tone occurs only when the part of the probe acting as the edge is within the shear layer.

Figure 4 shows the longitudinal mean velocity distributions across the plane free shear layer for $U_e = 37.2$ m/sec at three streamwise stations $x = 0.25, 1.35$ and

3.18 cm. The antisymmetric profile $U/U_e = 0.5 - 0.5 \tanh((y - y_{0.5})/2\theta)$, used by Michalke (1965) and Freymuth (1966) for spatial stability calculations, is also plotted for comparison. The asymmetry of the plane free shear layer velocity profile was observed by other investigators also (Liepmann and Laufer 1947, Hussain and Thompson 1975). Especially, the lack of agreement of the data with the tanh-profile at the low speed side can be attributed to a number of factors: large hot-wire errors at low velocities due to large fluctuation intensities and the transverse velocity, and the inherent changes in the profile due to its being in a state of relaxation from the boundary layer to the free shear layer profile.

The mean velocity profiles are not congruent, again, because the flow so close to the lip is still in a state of relaxation from the nozzle wall boundary layer (Blasius) profile to the error-integral type free shear layer profile. Note that if the profile U/U_e were plotted as a function of $y - y_{0.5}$ nondimensionalized by the shear layer vorticity thickness $\delta_\omega = U_e / (\partial U / \partial y)_{\max} = [\int_{-\infty}^{\infty} |\omega| dy] / |\omega|_{\max}$, a better congruence of the mean velocity profiles would be obtained (Hussain and Thompson 1975). Since the instability of the profile is sensitive to the profile details near the location of mean vorticity maximum (at $U/U_e = 0.5$), the vorticity thickness δ_ω , being determined by the profile at that location, is a more appropriate length scale than the momentum thickness θ which is insensitive to the profile details. However, due to differentiation of discrete data across a very thin layer δ_ω would have a larger uncertainty. For this reason as well as because of its widespread use by researchers in shear layers, the momentum thickness θ has been used as the length scale in figure 4. The rms total fluctuation intensity profile at $x = 1.35$ cm is also shown in this figure; note that the peak of the intensity u'/U_e occurs at the location of maximum of slope $(\partial U / \partial y)$, where fluctuation production $-\overline{p u v} \partial U / \partial y$ will be the highest.

The fundamental rms amplitude profile $u'_f(y)/U_e$ at $x = 1.35$ cm is also shown in figure 4; the minimum amplitude is consistent with the Kelvin's cat's eye type

flow associated with the motion of a vortex train over the hot-wire. The theoretically predicted amplitude variation according to the spatial theory of Michalke (1965) is also shown for comparison. The agreement on the location of zero amplitude is impressive; however, the amplitude variations away from this location does not agree. Similar data by Freymuth (1966), and Hussain and Thompson (1975) showed much closer agreement of the amplitude data with the theory, but the Strouhal numbers used by them were much lower. The phase profile data of Hussain and Thompson, however, did not agree with the theory; Freymuth did not present any phase data.

The disagreement between the data and the theoretical predictions can be due to a variety of factors: the mean velocity profile does not agree with the tanh-profile used in the theory; the flow is not parallel; there is a noticeable level of free-stream turbulence $u'_e/U_e = 0.003$; the theory is for infinitesimal (linear) disturbances while the velocity fluctuations involved in the shear layer tone are indeed large-amplitude (nonlinear). Another factor which will introduce some artifact in the data is inherent in the method of acquisition of the data. The probe, acting as the wedge, was also traversed in y in order to take the data. While this does not introduce any shift in frequency (see Figure 3) or wavelength, it would affect the measured amplitude distribution somewhat. The theory is based on inviscid fluid; consistent with the principle of Reynolds number similarity/invariance, however, the viscous effect can indeed be considered negligible since the shear layer Reynolds numbers are sufficiently large. Considering all these, the agreement between the theory and the data in figure 4 is reasonable.

The streamwise variations of the spectral peaks in figure 2 have striking similarity with slit jet-edgetone frequency data. The fact that hot-wires, as well as pitot probes, have been used in free shear layers by many investigators and that no previous investigator has reported probe induced edgetone effect

which can affect not only the instability frequency but also integral measures of the shear layer, prompted us to document the effect further. The frequencies of the spectral peaks (similar to those shown in figure 2) as the probe is moved downstream along the line with $U/U_e = 0.95$ in the plane free shear layer at five speeds including the $U_e = 37.2$ m/sec case of figure 2, are shown in figure 5 as a function of the axial distance x of the hot-wire. Note that around each frequency jump, there is an overlap region in which two spectral peaks occur. The overlap regions for the $U_e = 37.2$ m/sec case have been extended on either side of each jump (figure 5) as long as the smaller frequency spike could be distinguished from the background turbulence. For clarity, these overlaps for the other four speeds have not been shown; in each overlap region, frequency of the peak which has the higher amplitude of the two was chosen, thus defining a unambiguous jump frequency. As we will discuss later, the existence of two modes (i.e. two spikes) in the spectra in each transition (i.e. frequency overlap) region was observed to occur in one mode at a time only and not simultaneously. The tone flipped back and forth between the two modes but due to a large number (128) of ensemble averaging both the peaks appeared in the spectral plots in figure 2. Note also that with decreasing speed, the shear tone effect becomes irregular; this will be discussed in the next section.

The Roman numbers on this plot, shown only for the $U_e = 37.2$ m/sec case, indicate the stage of the tone, consistent with the nomenclature introduced by Brown (1937a). Data on the lower right-hand side of the plot (stage V) represent the subharmonic frequencies. Note that the subharmonic content in the spectra is quite broad with its peak value remaining essentially constant with downstream distance (figures 2 and 3). The subharmonic amplitude gradually decreases with increasing x until it is submerged in the evolving background turbulence.

3.1.1a Subharmonic frequency: No other edgetone study has reported the subharmonic formation. The presence of the subharmonic frequency observed in this study at all speeds is consistent with the phenomenon of vortex pairing, which has been the subject of extensive, recent research (Winant and Browand 1974, Brown and Roshko 1974, Hussain and Zaman 1975, Browand and Wiedman 1976, Zaman and Hussain 1977). A shear layer undergoes inviscid instability due to the inflexional profile; the disturbance grows downstream, saturates by nonlinearity and the flow rolls up into vortex rolls with spanwise vorticity. Such a vortex row is unstable (Lamb, 1945); any non-uniformity in the spacings or strengths of two (or three) adjacent vortices cause them to coalesce (pair up) and form a larger vortex. It has been suggested that most of the nonvortical fluid is entrained (ingested) during the pairing process which also is responsible for production of most Reynolds stress in a free shear layer. While essentially explaining the same phenomenon, Moore and Saffman (1975) presented a 'tearing' - as opposed to 'pairing' - mechanism for vortex interaction. Even though the details of the phenomenon of pairing is not yet well understood (Moore and Saffman 1975, Corcos and Sherman 1975, Brown 1976, Zaman and Hussain 1977) it appears that interactions like coalescence of large scale coherent structures play the key role in the evolution of these structures in free shear layers as well as jets, wakes and even, turbulent boundary layers.

It is remarkable that the organization of the flow due to edgetone feedback brings out the subharmonics associated with vortex pairing which otherwise would occur randomly in space and time and thus would not be clearly discernible from the velocity spectrum in a free shear layer without any edge or external excitation. After the occurrence of the first subharmonic starting at $x \approx 1.5\text{cm}$ in figure 2, note that another (broader) peak at half this subharmonic frequency arises at $x \approx 2.5\text{cm}$, indicating a second stage of vortex coalescence. The occurrence of

the vortex pairing (or tearing) ahead of the wedge suggests that only the coalesced vortices impinge on the wedge and thus provide feedback at the lip only at alternate periods of the shear layer unstable mode. Such alternate feedback along with the fact that the subharmonic occurs at large lip-wedge distances h would suggest that the effect of the feedback in triggering embryonic vortices at the lip would be inherently weak, and thus would produce some jitter in the location of its nonlinear saturation and roll-up, as well as in periods of impingement on the wedge. This would explain why the peaks at the subharmonic frequencies in figure 2 are weak and broadband. We have found that vortex pairing which otherwise occurs randomly in space and time (Brown and Roshko 1974, Winant and Browand 1974) can be organized and accentuated by controlled excitation at the appropriate Strouhal number (Hussain and Zaman 1975).

3.1.1b Axisymmetric free shear layer: To further confirm that the hot-wire probe produced the shear layer tone, similar hot-wire spectra measurements were taken in the free shear layer of a 2.54 cm diameter circular jet at three speeds; the ratio D/θ_e being large, the curvature of the axisymmetric configuration should not be of any significance. Frequency vs. axial distance curves for three speeds are plotted in figure 6. Note that at the locations of jumps, overlap regions exist but the overlap frequencies have been omitted by following the same procedure used for figure 5; evidence of coalescence resulting in a subharmonic peak was also found in these data but have not been shown in this figure. As to be expected, the detailed data in the axisymmetric free shear layer are similar to those in the plane mixing layer and are thus not shown further on.

3.1.2 Variation of frequency with jet exit speed: Variation of the probe induced plane free shear layer tone frequency with exit speed is documented in figure 7, which shows frequency spectra of the longitudinal velocity fluctuation $u(t)$. The hot-wire was placed at a fixed axial distance $x = 1.02$ cm inside the potential

core at the transverse location where $U/U_e \approx 0.95$. The plots are on linear-linear scales, the ordinates being arbitrary; the abscissa ranges 0-5 kHz, except for figure 7(i), which has 0-10 kHz range, and figures 7(xvii), (xviii) which span 0-2 kHz. Figure 7(i) confirms that there is no conspicuous spectral component on the higher frequency side; the last two show the details of the spectral content. The corresponding exit mean speed U_e is indicated on the right-hand side of each plot. As the speed is decreased, the frequency of the spike in the spectra decreases and a jump to a lower frequency occurs at about $U_e = 36.6$ m/sec; the discussion of the sequence of events as the speed is reduced further would be similar to that of figure 2.

At lower speeds, the clear sharp spikes that characterized the spectra at higher speeds degenerate into a band of small-amplitude spectral components many of which could be identified as characteristics of the jet flow facility, such as, the settling chamber cavity resonance, the blower blade passage frequency (172 Hz) etc. These spectral peaks, characteristic of the jet facility, tended to persist to some extent as the exit speed was changed. In order to avoid possible ambiguity between these frequencies and the shear layer tone frequencies at low speeds, the study of $U_{e_{min}}$ as a function of h was not pursued.

The probe induced free shear layer frequencies as read from plots of figure 7 and from spectra at intermediate speeds are plotted in figure 8 as a function of exit speed U_e . Overlaps at the transitions are shown; the amplitudes of the stage I spectral components could never exceed those of stage II; because of the low amplitudes of shear layer induced velocity in stage I and of 'contamination' of the spectra by settling chamber cavity resonance modes, as discussed above, stage I could not be explored at still lower speeds. The circles in this figure show data obtained when the speed was increased; the triangular data points were

obtained with the speed decreasing. These data showed absence of hysteresis, typical of the jet-wedge edgetone (to be discussed in section 3.2.1).

3.1.3 The effective wedge on the probe body: Having discovered the principal symptoms of the hot-wire probe induced free shear layer tone, it was considered worthwhile to determine which part of the probe support acted as the effective wedge in these cases. From the sketch of the probe in figure 1(b), edges 1 and 2 appeared possible candidates. We found that slight changes in the shape of edge 1 by wrapping a cellophane tape around it significantly changed the spectrum of the hot-wire signal while similar changes in edge 2 produced no effect. This strongly suggested that edge 1 on the probe support was acting as the wedge.

The location of the effective wedge on the probe was confirmed further by putting a 20-degree wedge in the flow (figure 1c), and measuring the frequency variation of the resulting tone with axial distance of the wedge. The frequency as a function of the jet lip-wedge distance (for the plane free shear layer at $U_e = 37.2$ m/sec) is plotted in figure 9. The frequency in this case was obtained by putting the hot-wire probe on the outer edge of the shear layer i.e. at $U/U_e \approx 0.20$ while the probe stem was inclined at an angle of 60° with the axial direction so that the probe edge itself produced no disturbance. The axial location of the hot-wire was immaterial because the frequency sensed by the hot-wire for a fixed location of the wedge was found to be constant everywhere in x . The hot-wire probe induced shear layer tone data are replotted in figure 9 by shifting the data from figure 5 (for $U_e = 37.2$ m/sec) to the right by 0.737cm so that h now represented the distance of edge 1 from the lip. Probe induced edgetone data, thus shifted, agreed with the wedge data most closely. We confirmed that edge 1 was the source of edgetone from the probe.

However, the frequency variations in stages III and IV for the probe case and the wedge case remain different. It was observed that the third and fourth stage tones for the wedge case was 'distorted' and the spectra were characterized by strong higher harmonics of the fundamental edgetone spectral component. In the 1st and 2nd stages, however, the velocity spectrum had a single, unambiguous peak. The differences between the frequency variations of the probe and the wedge in the third and fourth stages remain unexplained, the differences in the shapes and sizes of the two may be the reason.

Note that equation (1) based on the slit-jet edgetone does not represent the frequency variation in a shear layer tone as shown in figure 9. The data of Sarohia (1976) are also shown for comparison.

3.1.4 The most sensitive disturbance frequency for a shear layer: The sharp peaks in the hot-wire signal spectra disappear when the probe is moved to the outskirts of the shear layer. Figure 10 shows frequency spectra plots with the hot-wire placed at the y-location in the plane free shear layer where $U/U_e \approx 0.10$, the probe axis making an angle of 60° with the mean velocity so that the disturbances generated by the probe support was minimal; these data were taken at $U_e = 37.2$ m/sec. Although there is no sharp peak in these plots, there is an unambiguous hump in each, the peak frequency of which remains constant within an axial distance in which at least two edgetone stages would be found if the probe support were in the shear layer. The broadband humps can be explained by the argument that, although there is no controlled external disturbance, there exists the 'white' background noise from which the disturbances with frequencies in the unstable band are picked up and appropriately amplified by the shear layer. The peak of these humps should represent the most sensitive frequency. Figure 10 thus shows that the plane free shear layer under study is most sensitive at about 3280 Hz when $U_e = 37.2$ m/sec.

This frequency is also midway in any stage of edgetone frequency variation with x at $U_e = 37.2$ m/sec (figure 5). As shown in figure 2, the rms amplitude of the edgetone spectral component in any stage reaches its maximum somewhere in the middle of the stage. For $U_e = 37.2$ m/sec, maximum edgetone induced velocity amplitude was measured at $f = 3280$ Hz.

We thus conclude that data on the sensitivity of shear layers to external disturbances should be obtained with the probe placed such that no sizeable part of it intersects the shear layer. A sharp peak in the spectra of the velocity signal from a hot-wire in a thin shear layer should be interpreted with caution. The frequency of the probe induced tone may differ significantly from the natural roll-up frequency of the shear layer; note that the spectral peak frequency varies from about 2900 Hz to 3900 Hz for $U_e = 37.2$ m/sec depending on the probe location (figure 9) while the instability or natural roll-up frequency is 3280 Hz. The occurrence of an edgetone can also noticeably alter the mean shear layer characteristics as well as its coherent structure and thus its subsequent evolution. An alternative way of determining the most unstable frequency for a shear layer could be to change probe position in x and identify the edgetone frequency component which produces the largest amplification of velocity fluctuation amplitude. Another option would be, of course, to employ noninvasive measurements like the laser-Doppler velocimetry; in this case, however, apart from the space and price limitations, the large scattering volume would not provide shear layer data with fine spatial resolution.

3.2 On the aspects of free shear layer tone

3.2.1 Near-parallel shear flow theory: The linear hydrodynamic stability theory for the propagation of small amplitude disturbances in a parallel shear flow predicts that the frequency of a normal mode experiencing the maximum amplification in a

given shear layer is unique. However, due to viscous diffusion of vorticity (i.e. entrainment), free shear layers are not parallel; when the non-parallel effect is taken into account, a continuous decrease in the frequency of the most sensitive mode with increasing x is predicted (Woolley and Karamcheti 1974, Ling and Reynolds 1973). Clearly, the frequency of such an instability mode at any streamwise location scales with the local shear layer thickness, which can be characterized by the profile width $B = y_{0.95} - y_{0.1}$, or the momentum thickness $\theta = \int_{0.1}^{\infty} (U/U_e)(1 - U/U_e)dy$ or the vorticity thickness δ_ω , each of which continuously increases downstream; $y_{0.95}$ and $y_{0.1}$ are the locations at which U/U_e is 0.95 and 0.1, respectively. Thus when either B or θ or δ_ω is used as the length scale there should be a continuous decrease of the 'most unstable' frequency in the downstream direction.

Woolley and Karamcheti (1974) have shown that some of the main features observed in jet edgetone, such as decreasing frequency with increasing jet-wedge distance, can generally be explained by the non-parallel effect. However, they have not addressed a major feature of edgetone, namely the frequency jumps. If non-parallel flow theory were to explain the decrease in frequency with axial distance in edgetone, the local shear layer thickness would be the relevant length scale governing the instability mechanism, since the characteristic velocity scale U_e remains unchanged. Thus, the Strouhal number based on B , θ or δ_ω should be expected to have similar functional relationship in the different stages of edgetone operation. The following data clearly indicate that such is not the case.

For $U_e = 37.2$ m/sec, the streamwise variations of the plane free shear layer momentum thickness θ and vorticity thickness δ_ω were obtained from mean velocity profile traverses with the help of the on-line laboratory minicomputer. Figure 11

shows the variations of θ and δ_ω with x as obtained from the mean velocity profiles by traversing the single wire probe only. In such measurements the effect of the transverse component of the mean velocity on the zero-speed side of the free shear layer introduced uncertainty. Instead of adopting any correction procedures - which are all questionable - to smooth out the zero-speed side tails of the mean velocity profiles, we truncated the integration for θ at $U/U_e = 0.1$. The vorticity thickness measured on the basis of the maximum slope of the mean velocity profile by least square fit of a straight line passing through four data points around the half mean velocity point is unaffected by this truncation. However, θ , being an integral quantity, exhibited much lower uncertainty compared to δ_ω ; the latter was determined within an uncertainty of $\pm 5\%$. The oscillations in $\theta(x)$ are attributable to the different stages of edgetone.

Also included in figure 11 is the streamwise evolution of the 'free shear layer shape factor' δ_ω/θ which has a value of about 5 for $x/\theta_e \leq 80$, but about 4 for larger values of x/θ_e . This abrupt change in δ_ω/θ should indicate an inherent change in the profile i.e. a sudden widening of the shear layer and thus may indicate the location for roll-up of the free shear layer. The flow dynamics of the free shear layer before and after the roll-up are quite different, there being larger entrainment after roll-up. The oscillations in the $\theta(x)$ indicate effects of successive stages of edgetone on shear layer entrainment at 0.75cm ahead of the wedge. The average value of $d\theta/dx = 0.048$ is higher than Sarohia's (1976) values ranging up to 0.022. The values of $d\theta/dx$ in the self-preserving region of a shear layer was found to be 0.035 by Liepmann and Laufer (1947) and 0.030 by Hussain and Zedan (1977). This difference may be explained by the fact that $\theta(x)$ in figure 11 does not represent streamwise change of θ in a particular shear layer under tone with a fixed wedge

but successive $\theta(x)$ in front of the wedge as it is moved downstream. Further, the free shear layer adjacent to the lip here is far upstream from the self-preserving region studied by Liepmann and Laufer (1947) and Hussain and Zedan (1977).

The data of figure 11 coupled with the frequency data of figure 5 (for $U_e = 37.2$ m/sec) were used to obtain local Strouhal numbers based on θ and δ_w . The variations of St_θ and St_{δ_w} in the different stages are shown in figures 12a and 12b, respectively. The indicated stages denoted by the Roman numerals correspond to the edgetone stages.

Figures 12a and 12b show that neither St_θ nor St_{δ_w} remains constant in any of the stages; however, they vary much less in the first two stages. The functional dependence of these quantities on axial distance x from the lip are quite different for the different stages. The variations lead us to believe that the instability mechanism in free shear layer tone does not scale on its characteristic length scale like momentum or vorticity thickness and thus it would appear that near-parallel flow theories alone cannot explain the pattern of frequency variation even in one stage of operation. Clearly, feedback from the wedge being central to the shear layer tone mechanism, other length scales such as the lip-wedge distance h , and time scales like h/U_e , vortex transit time from lip to wedge, disturbance feedback time from wedge to lip etc. must be important along with the nonparallel effect in controlling the edgetone behavior.

3.2.2 The amplitude variation in the different stages: All the data reported hereinafter pertain to edgetone in the plane free shear layer created by the wedge as described before (figure 1). The audio tone produced by the wedge was much louder than that produced by the probe.

The vortex formation at the tip of the wedge is two-dimensional and the vortex will be stronger for the wedge than for the probe. These, together with the fact that the wedge has a larger radiating surface would explain the louder

tone produced by the wedge. The lip-wedge distance being much smaller than the sound wavelength, the edgetone phenomenon is indeed a near-field effect and thus would depend on the shape and size of the wedge.

The loudness of the tone was also extremely sensitive to the transverse location of the wedge in the free shear layer. The edgetone was loudest when the wedge was placed approximately at the half mean velocity point in the shear layer. Slight transverse displacement of the wedge from this point would make the audio tone strength drop drastically. Note that the shear layer thicknesses involved are extremely small (see figure 11), much smaller than a typical wedge width. While the transverse location of the wedge tip strongly affects the shear layer tone amplitude, fortunately the frequency of the tone is not very sensitive to the transverse location of the probe or the wedge (see figure 3). The peaks in the hot-wire velocity signal spectrum can be clearly identified even when the tone cannot be heard.

In the available literature on jet edgetone, hysteresis at the locations of frequency jumps had been observed to be a universal characteristic of the edgetone phenomenon (Brown 1937a, Curle 1953, Powell 1961, Karamcheti et al. 1969). That is, the transitions shown by the dotted lines in figure 5 and locations of frequency jumps in figure 8 would be different when the value of the independent variable - either h or U_e - is increased as opposed to the case when it is decreased. In the probe edgetone data, however, we could not find any evidence of hysteresis in the overlap regions; careful repeats confirmed this observation. Multiple modes as shown in figures 2 and 7 were not associated with hysteresis i.e. the relative amplitudes remained the same whether the speed U_e was being increased or decreased or whether h was increased or decreased. Figures 13, 14 not only

demonstrate the nonexistence of hysteresis in shear layer tones produced by the wedge but also throw further light on the physics during the frequency jumps. The differences in the amplitude distributions for the probe and the wedge also provides some interesting insights. For brevity, probe induced tone velocity amplitude variations with h or U_e are not shown.

The rms amplitudes of the shear layer tone spectral components as a function of the exit speed U_e for two wedge locations - 1.22 cm and 1.83 cm - are presented in figure 13. The hot-wire was placed between the lip (i.e. the separation point) and the wedge, at fixed locations (different for the two cases) and at a large angle α with the shear layer plane so that the probe body itself produced no interference. The solid data points in this plot represent those obtained while U_e was being increased and the open data points were obtained while U_e was being decreased, each run lasting about an hour. The stages indicated in the figure were determined from cross-plots of the associated frequency data as a function of nondimensionalized axial distance h/θ_e (see sec. 3.2.4).

As can be seen from figure 13, the amplitudes of the spectral components at any exit speed are functions of the lip-wedge distance and except for the unavoidable scatter in the data, are unique functions of the exit speeds themselves regardless of whether the speed U_e was increased or decreased; thus no evidence of hysteresis was observed.

Unlike in the probe induced tone where the frequency overlap region covers a reasonably large range of U_e (figure 8), the transition between the stages for the wedge case occurred rather abruptly and it was difficult to capture both spectral peaks simultaneously in the velocity spectra. However, with very slow change in the velocity U_e we could obtain values of U_e at which two modes occurred

intermittently and the resulting time averaged spectrum exhibited the two spikes corresponding to the two stage frequencies. Careful observation of the scope trace revealed that the signal frequency changed intermittently from one to the other, but never both occurring simultaneously. Observations of the 'real time spectra' (i.e. single realizations of the frequency spectrum) clearly showed that the velocity spectrum had only one peak for each realization while a large ensemble average contained both the peaks. Our observation that the shear tone in the overlap region occurs in one mode only at a time contradict other investigators' results that both modes in an overlap region of edgetone occur simultaneously (Brown 1937a, Powell 1961, Bilanin and Covert 1973, McCanless and Boone, 1974). However, Sarohia's (1976) observation agrees with ours.

Amplitude distribution in the different stages of the edgetone as a function of axial distance h is shown in figure 14. The two sets of curves represent the following two cases: (a) the hot-wire placed at a fixed distance 0.16 cm in front of the wedge and moved along with the wedge; (b) the probe was fixed in the flow at a distance $x \approx 0.62$ cm downstream from the lip and at the transverse location where $U/U_e \approx 0.95$ while the wedge was traversed in x . Amplitudes for up to the third stage have been documented. In this figure, the solid data points represent those taken while h was being decreased and the open data points represent those while h was being increased, the run for each of the two cases lasting approximately an hour. The data for both forward and backward movement of the wedge, for both the cases (a) and (b), again, follow the same smooth curves and no evidence of hysteresis could be found.

Powell's (1961) theory predicted that the hysteretic jumps in slit-wedge edgetone resulted from nonlinearity associated with the large amplitude fluctuations in the edgetone flow. During transition, a harmonic content in the established

motion in a stage was presumed to provide stimulus for jump to the next stage and a distinct jump thus occurring would 'more likely than not' be hysteretic. The lack of hysteresis in our data is currently being further investigated. It is noteworthy, again, that Sarohia (1976) in his study also found no evidence of hysteresis.

Comparison of data in figures 13 and 14 with the probe induced amplitude variation data (not presented), shows that the bimodal (overlap) region for the probe induced tone is broader than for wedge case. The probable explanation may be that in the case of the sharp edged wedge, the wedge-tip generated vortex is stronger and the induced circulation at the lip (as well as the radiated sound intensity) larger due to the stronger vortex and the larger wedge surface area, so that the feedback is more pronounced in the wedge case. The flow then has lesser ambiguity in determining the optimum wavelength or frequency.

The relatively higher amplitudes in figure 14(a) is due to the axial growth of the disturbances as the probe is moved in the axial direction. Thus amplitude variation in any stage in case (a) is not only dependent on whether the tone frequency falls near the most sensitive disturbance frequency (which receives maximum amplification) within the unstable frequency band but also due to the fact that with increasing h longer streamwise distances are permitted for the disturbance to grow to larger amplitudes. Case (b), where the probe has been held at a fixed point in the flow field, thus represents the growth and decay of the edgetone flow oscillation amplitude depending on whether the shear layer tone frequency is approaching or receding from the most sensitive disturbance frequency of the free shear layer. From streamwise distribution of the shear layer tone induced amplitudes (not presented) we know that the amplitude increases in x reaching its

maximum at about $0.85h$ from the lip. Thus case (b) above should produce lower amplitudes (see figure 14).

As the wedge was moved upstream very close to the lip, the spectral peak component rms amplitude progressively decreased (the frequency, of course, changing simultaneously) until it became obscured by the background turbulence. Although the amplitude variation at the beginning of the 1st stage in figure 14 is monotonic, the sharp rise in the amplitude (as h is increased) indicates the existence of a minimum lip-wedge distance $h_{\min}$ for the tone to occur.

Likewise in figure 13, the inter-stage transitions in figure 14 occurred over a small distance unlike the case in probe induced edgetone (not shown). Even though the ensemble averaged spectrum showed peaks corresponding to both the stages during transition, careful scrutiny revealed that the edgetone occurred in only one mode at a time while intermittently switching between the two stages. It is to be noted that, the subharmonic spectral peaks shown in connection with the probe induced edgetone, did not occur in a similar 'one or the other mode' with the fundamental edgetone component. The oscilloscope trace indicated the signal to constitute alternately stronger and weaker wave crests at the period of the fundamental and thus producing the subharmonic spectral peak. A subharmonic in a spectrum in these situations indicates vortex pairing and thus the generation of the subharmonic further downstream in the tone flow is due to vortex pair-up in the free shear layer (Zaman and Hussain 1977). Higher harmonics in the spectra of the wedge induced tone velocity signal in stages III and IV resulted from the large-amplitude distorted wave form; and these spectral peaks at higher frequencies have no physical significance.

3.2.3 Spanwise extent of shear layer tone: The presence of the 1.27 cm wide wedge in a plane free shear layer of 140 cm span raised the question as to whether

the wedge was introducing instability over the entire span of the shear layer. Thus it was necessary to determine the spanwise extent of the wedge induced shear layer tone. The hot-wire was traversed in the spanwise direction at constant x and y . The spectra of the velocity signal for different spanwise positions of the hot-wire relative to the wedge were obtained. It was found that for a fixed wedge location, the tone frequency did not vary in the spanwise direction. The amplitude of the spectral component at the tone frequency, however, decreases sharply as the hot-wire is moved away from the wedge. The edgetone spectral peak rms amplitude as a function of the spanwise distance of the hot-wire from the wedge is shown in figure 15. As can be seen, the spike in the spectra is almost lost at about 10.2cm away from the wedge. Note that this distance is considerably shorter than the 140cm span of the plane free shear layer. Thus, the wedge did not precipitate instability of the shear layer over its entire span; the observed shear layer tone phenomenon is clearly a localized event.

3.2.4 The characteristic length scales of the phenomenon: The nondimensional frequency $St_h (= \frac{fh}{U_e})$ are plotted in figure 16 as a function of h for four different cases. These four cases are: (i) variable U_e with wedge at $h = 1.22\text{cm}$, (ii) variable U_e with $h = 1.83\text{cm}$, (iii) variable h with $U_e = 43.3 \text{ m/sec}$ and (iv) variable h with $U_e = 29.3 \text{ m/sec}$. For the two constant h cases i.e. cases (i) and (ii), the data obviously fall on vertical lines while for the other two cases, St_h can be found to increase nearly linearly with h . The shear layer tone data thus differ from the slit-wedge edgetone data of different investigations, where St_h has been observed to remain constant in each stage, the values being approximately 0.5, 1.1 and 1.7 in the 1st, 2nd and 3rd stages, respectively (see Karamcheti et al. 1969).

The differences between the present data and the jet edgetone data are not unexpected because of the differences in the velocity profiles; the latter studies involved slit-jets with fully developed (parabolic) exit mean profiles, while the plane free shear layer has an error integral type profile (figure 4). The instability, roll-up and the disturbance growth in x in the two cases are different. Apart from the imposed length scale h (the slit-wedge distance), the length scale associated with the instability mechanism for slit-jets is the slit width H , while such a configuration-imposed length scale does not exist in the free shear layer. Thus it is to be expected that the slit-wedge edgetone frequency variation data will collapse on the same horizontal line for a particular stage on a St_h vs h/H plot; on the contrary, since H is no longer a length scale in a free layer tone, the differences between the different sets of data in figure 16 are to be expected. Figure 16 thus suggests the need for an appropriate length scale. Note that Sarohia's (1976) data also show almost linear variation of St_h with h in each stage and agree qualitatively with ours.

For the free shear layer, the profile defines a length scale of its own. This can be either the initial momentum thickness θ or the vorticity thickness δ_w ; either will suffice as the appropriate characteristic length scale of the free shear layer. One can thus expect that if a characteristic initial shear layer thickness (eg. θ_e) is chosen as the length scale, the free shear layer tone nondimensional frequency variation for each stage may be universal.

A number of data points for the exit shear layer momentum thickness (θ_e) as a function of the jet exit speed U_e were obtained. Least-square fit of different forms of curves through these points gave a curve of the form $\theta_e/H = a(R_{eH})^b$ with $a = 0.4814$ and $b = -0.4182$ respectively. This θ_e vs U_e curve was later used to obtain exit momentum thickness θ_e at any exit speed U_e .

The frequency (St_h) data shown in figure 16, when plotted as a function of h/θ_e , were found to fall on the same smooth line for each stage. This is shown in figure 17a. These data also collapse on one another if plotted on a St_{θ_e} vs h/θ_e plot, as shown in figure 17b. Note that the coordinates St_{θ_e} vs h/θ_e in figure 17b not only makes the four sets of data collapse but also the ordinate variations in the three stages are brought in the same range.

Figures 17a, b clearly point out the importance of initial shear layer thickness as a scaling parameter in the free shear layer tone. The congruence of non-dimensional frequency data in each stage for four independent cases suggest that for each stage, both St_{θ_e} and St_h are universal functions of the ratio of the two length scales of the problem viz., h and θ_e . Thus either of the two figures 17 a, b can be used to predict the shear layer tone frequency for any combination of h and U_e for a particular free shear layer. That is, provided the variation of θ_e as a function of U_e is known for a free shear layer in a given configuration, one should be able to predict from figure 17a or 17b the free shear layer tone frequency at any h for each U_e or at any U_e for each h . Figures 17a, b are thus the key figures capturing the physics of the free shear layer tone phenomenon.

3.3 Shear layer tone eigenvalues and eigenfunctions

The free shear layer tone study would be incomplete without an understanding of the tone induced velocity amplitude variations across the layer, as well as the dependence of the wavenumber and phase velocity on the tone frequency. These data would represent the eigenfunctions and the eigenvalues of the shear layer tone flow; a successful shear layer tone theory must be able to predict these eigenfunctions and eigenvalues given the flow parameters viz., h , U_e , θ_e etc. These measurements were done in the plane free shear layer at the values of U_e : (i) 29.3 m/sec, (ii) 37.2 m/sec and (iii) 43.3 m/sec with the plane wedge. For a fixed wedge location at a constant U_e , a reference hot-wire probe was placed at a fixed location in the flow (figure 1(a)). The edgetone frequency was determined from the spectrum of the reference probe signal.

The lock-in-amplifier was then tuned (calibrated) at this frequency. The signal from the reference probe was (narrow) band-pass filtered before it was used as the reference signal in the lock-in-amplifier. The velocity signal from the second probe in the flow field (figure 1a) was analyzed by the lock-in-amplifier which determines the relative phase of the shear layer tone induced velocity component at that point with respect to the reference probe signal. Since at any stage of shear layer tone production the fluctuation velocity frequency is the same everywhere (figure 3), the variations of the phase of the shear layer fundamental component was found as a function of space coordinates by traversing the hot-wire probe in x and y . The whole procedure was repeated for other shear layer tone frequencies obtained by changing the axial location h of the wedge and by changing U_e .

3.3.1 Shear layer tone amplitude and phase profiles: The transverse variation of the phase of the tone induced velocity fluctuation across the plane shear layer is plotted in figure 18a, for three axial locations of the signal probe viz., $x = 0.51$, 0.76 and 1.02 cm, for $U_e = 37.2$ m/sec. This figure corresponds to the wedge fixed at $h = 1.40$ cm and the tone frequency of 3500 Hz. Note that the half mean velocity point i.e. $U/U_e = 0.5$ is located at $(y-y_{0.5})/\theta = 0$. All the three figures have the same abscissa and ordinates, but the figures are shifted vertically by arbitrary amounts in order to avoid overlaps. The arrow indicates the vertical scale for each plot.

The dotted curve represents the theoretical phase prediction according to the spatial stability theory (Michalke 1965, Freymuth 1966) corresponding to the station $x = 1.02$ cm. Even though the details of the theoretical profile do not agree well with the data, the agreement on the location and extent of phase jump is impressive. Other reasons for disagreement between the data and the stability theory were discussed in connection with figure 4.

Figure 18b shows the profiles of the rms amplitude of the tone induced velocity fundamental u'_f corresponding to the three phase plots shown in figure 18a. The

nondimensional amplitudes u_f'/U_e are plotted in dB to enable easy comparison with figure 4, which shows one such profile for the case when the probe is acting as the effective wedge. Note that the tone velocity amplitudes increase in x . The data in figure 18b were obtained to check the speculation made while discussing the data of figure 4 that, compared to the probe induced tone case, the plane wedge induced tone velocity amplitude profile will agree more closely with the spatial stability theory prediction. In spite of the various reasons for expecting discrepancy between the theory and the data (discussed in sec. 3.1.1), the agreement on the location of the notch in figure 18b and on the location and extent of the phase jump in figure 18a for the $x = 1.02$ cm case is very good.

3.3.2' Phase velocity and wavenumber: From the phase profiles in figure 18a, the difficulties encountered in phase velocity measurements should be obvious. Due to large transverse phase gradients, the uncertainty in phase velocity measurements, unless done judiciously, can be excessive. For example, the phase velocity, when calculated from phase data on a $y = \text{constant}$ line, would vary from that determined along a $U/U_e = \text{constant}$ line.

The following criterion was adopted for finding the phase velocities of the edgetone velocity disturbances in the shear layer. Corresponding to a fixed location of the wedge, the signal hot-wire probe was traversed in y at each x station to find the maximum phase ϕ_m at that x . The rate of change of this maximum phase with axial distance, $d\phi/dx$, was then found over a short axial distance Δx covering at least six closely placed data stations. The variation $\phi(x)$ was observed to be linear within the axial distance $0.50 \text{ cm} < x < 0.9 \text{ cm}$, with the reference probe held fixed at $x = 0.914 \text{ cm}$. A mean straight line through the phase data at six stations within this x -range gave the rate of change of the phase with axial distance, $d\phi/dx$, from which the phase velocity was determined.

The shear layer tone induced velocity wave characteristics can be determined from the assumption of a spatially travelling vorticity wave (Lin 1955, Hussain 1969, Hussain and Reynolds 1972) in a free shear layer which acts as the waveguide, the wedge providing the stable feedback. While instability of the shear layer appears to be a central factor in the edgetone phenomenon, figures 18a, b show that the measured wave characteristics do not truly represent a (single) normal mode. However, for the purpose of determination of the wave characteristics of the shear layer tone, the nonparallel aspect will be ignored and the measured quantities will be assumed to represent a spatially dependent normal mode. Thus we can represent the instantaneous longitudinal velocity fluctuation u due to an edgetone mode as

$$u(x,y,t) = \frac{1}{2}[\hat{u}(y)e^{i(\alpha x - \omega t)} + \text{complex conjugate}] \quad (3)$$

where $\hat{u}(y)$ is the complex amplitude distribution in the transverse (y) direction, $\alpha = \alpha_r + i\alpha_i$ the complex wavenumber and $\omega/\alpha = c$ is also complex i.e. $c = c_r + ic_i$, the measured phase velocity or celerity being given by $v_c = \omega/\alpha_r$. Note that figure 18b shows the amplitude profiles $|\hat{u}(y)|$ at three stations in the shear layer tone flow. When normalized by the peak values, the three amplitude profiles would indicate a certain extent of streamwise homogeneity, thus justifying essentially parallel flow assumption.

Within the approximation stated above, it is now possible to estimate the propagating wave characteristics (α_r or λ , α_i , u_c) from the hot-wire data. From equation (3), it follows that at two streamwise locations x_1 and x_2 , both at the same y-location,

$$\frac{u(x_2, y, t)}{u(x_1, y, t)} = e^{-\alpha_i(x_2 - x_1) + i\alpha_r(x_2 - x_1)} \quad (4)$$

Denoting the phase of u by ϕ_u

$$\phi_u(x_2, y, t) = \phi_u(x_1, y, t) + \alpha_r(x_2 - x_1) \quad (5)$$

We find λ as

$$\lambda = \frac{2\pi}{\alpha_r} = \frac{2\pi(x_2 - x_1)}{\phi_u(x_2) - \phi_u(x_1)} \quad (6)$$

The same edgetone frequency can be obtained in either stage I or stage II by properly locating the wedge in the axial direction. For four such frequencies at $U_e = 37.2$ ms/ec it was found that the phase velocity was dependent on the frequency alone and not on the stage of the tone. This is shown in Table 1 which shows negligible dependence on stage of the phase velocity as well as the wavenumber. For all these data the reference probe was kept fixed at $x = 0.914$ cm while the signal probe was traversed from $x = 0.50$ cm to $x = 0.9$ cm with increments of about 0.08 cm to obtain six data points for the

phase variation. As already discussed, the y -location of the signal probe was slightly adjusted at each x -station in order to locate the maximum phase; these y -adjustments being extremely small, the line connecting the maximum phase locations may be regarded as essentially at constant y . Note that the phase profiles in figures 18a, b cover an x -range smaller than that used in the determination of v_c and λ .

The phase velocities v_c were then found for different frequencies spanning the range available for the first stage of operation as indicated in figure 5. The v_c data were nondimensionalized by exit mean velocity U_e and plotted as a function of frequency in figure 19a. With the same considerations and measurement procedures described for $U_e = 37.2$ m/sec case, similar phase velocity data were obtained at two other speeds and are also shown in figure 19a. Note that for the first two stages of the $U_e = 37.2$ m/sec case the v_c data are independent of the stage but depend only on f .

In the different works on shear layer instabilities and organized structures, (e.g. Browand and Laufer 1975) comparable values of phase velocities were reported. The monotonic decrease of the disturbance propagation velocity with increasing disturbance frequency is interesting. The disturbances at the most sensitive frequency, namely, 3280 Hz for $U_e = 37.2$ m/sec as discussed in section 3.1.4 has a phase velocity corresponding to $U_c/U_e = 0.58$. Disturbances having frequencies lower than this move faster while those with higher frequency propagate comparatively slowly. Similar statements can be made for the other two speed cases (figure 19a).

The shear layer tone wavenumber as a function of frequency are plotted in figure 19b for the first stages of the same three cases used in figure 19a; we have used θ_e as the appropriate length scale for nondimensionalization of the

data in this figure. One can see that, in each stage, the wavelength increases with decreasing frequency. The theoretical predictions based on the spatial and temporal instability theories of Michalke (1965) for the same St_{θ_e} range are also shown for comparison. As stated earlier (section 3.1.1), there are various differences between the theory and the real flow; any of those could explain the lack of agreement between the wavenumber and phase velocity data and theory (figures 19a, b). However, the trend of the data appears to agree qualitatively with the spatial instability theory. Note that Freymuth's (1966) data in a free shear layer under excitation agreed with the spatial theory at lower Strouhal number St_{θ} but with the temporal theory at higher St_{θ} . On the other hand, Crow and Champagne (1971) found close agreement of their experimental eigenvalue data with the temporal theory. While the spatial theory is expected to be the appropriate one for our experiment, it may still be unable to predict the data. When the nonparallel nature of the mean flow is taken into account in the spatial theory variations of v_c/U_e and $2\pi\theta_e/\lambda$ with St_{θ_e} would agree with the data more closely than shown in Figures 19a, b (P. J. Morris, private communication).

Since the phase velocity and wavelength are found to be unique functions of the free shear layer tone frequency in each stage, a cross-plot of v_c/U_e as a function of h (or U_e) would show a jump in v_c and λ at the location of a frequency jump. That is, as h is increased at a fixed U_e , both λ and v_c will increase monotonically in each stage, then drop at the start of the next stage. This result is in contrast with the data presented by Sarohia (1976) who found a smooth variation of the phase velocity during a frequency jump. For a particular stage of operation, however, the increase in phase velocity with decreasing edgetone frequency in our data is in qualitative agreement with Sarohia's data.

The gradual decrease of phase velocity with increasing f (i.e. decreasing h) would indicate that the feedback from the wedge to the lip is not acoustic. If the feedback were acoustic, the time required for the feedback to reach the lip

would be larger and consequently, a decrease in the apparent convection velocity will be observed with increasing h .

3.3.3 The h - λ relation: The values of h/λ as a function of the normalized frequency St_{θ_e} for the three speed cases namely $U_e = 29.3, 37.2$ and 43.3 m/sec are shown in figure 20 for the first two stages.

That the ratio h/λ is not a whole number was shown by Brown's (1937a) data which however, showed that h/λ was approximately a constant in each stage of operation. Curle (1953) hypothesized from different available data on edgetone including Brown's that the ratio bears a relationship of the form of equation (2). The present data in figure 20 show that the ratio is essentially a constant in each stage; however, there is a slight increase with increasing frequency, the rate of increase being higher for stage II. The mean value of the quantity h/λ in stage I is about 1.6 while that in stage II is about 2.5; thus the constant in the free shear layer tone is different from 0.25 in the Brown-Curle equation (2) for jet edgetone. One should remember that the present study is on single free shear layer tone, the instability mechanism in which, as discussed before, differs from that in a jet edgetone phenomenon. Note that, Sarohia's (1976) data, are in good agreement with our results (figure 20).

IV. SUMMARY AND CONCLUSIONS

The hot-wire probe has been found to induce stable free shear layer oscillations through the edgetone mechanism. It is surprising that no previous investigator has reported this unavoidable edgetone effect in near field free shear layer measurements involving hot-wires. This effect can be significant also in measurements involving large-scale organized structure, conditional sampling, space-time correlation, convection velocity etc, when a reference or indicator probe may be used near the

the origin of the free shear layer. Since the probe can induce and organize initial instability, it can thus dominate: the shear layer roll-up into vortices, the subsequent nature and number of vortex coalescences and thus the downstream large-scale coherent structure as well as the shear layer integral measures like spread rate and virtual origin.

It appears that even in a free shear layer without any wedge, an object in the flow sufficiently downstream can also provide feedback to the flow upstream. In fact, the influence of the detection hot-wire on the vortex shedding behind a cylinder, observed by Kovasznay (1949) and others, may be due to the shear layer tone feedback effect studied here. On the other hand, in a turbulent free shear layer in an unbounded space the coherent structure at a location can be the result of organization by feedback from the coherent large scale structures further downstream (Dimotakis and Brown 1976, Naudascher 1967).

The present study should caution against unsuspecting use of invasive probes including pitot tubes in the near fields of free shear layers. Use of a probe like a pitot or a hot-wire will also affect the mean properties like streamwise variation of momentum and vorticity thicknesses, entrainment rate etc. of the shear layer due to the occurrence of probe induced edgetone. These shear layer mean properties are dependent on edgetone Strouhal numbers.

Thus invasive probe measurement near the origin of a free shear layer can provide misleading information. For example, the frequency measured by a hot-wire in the free shear layer can vary significantly from the most unstable frequency, the measured frequency being determined by the lip-probe distance. To measure the most unstable frequency one has to vary the lip-probe distance gradually and identify the distance - thus the frequency - producing the largest amplification of the velocity perturbation.

Since no previous study of the free shear layer tone could be found, it was considered worthwhile to investigate this phenomenon. Thus, the characteristics of the shear layer tone phenomenon induced by a hot-wire probe were determined in the near field free shear layers of incompressible plane and circular air jets. It is found that the hemispherical front end of the probe stem at the base of the hot-wire supporting prongs acts as the effective wedge producing the shear layer tone. The data in the axisymmetric and plane free shear layers gave the same results, as to be expected; thus, only plane shear layer data have been presented.

The inherent differences between the rolled-up vortex patterns in a slit jet and a free shear layer and their presumed key role in edgetone production justified an exploration of the shear layer-wedge tones and comparison of the data with those of slit jet-wedge edgetone.

The characteristics of the probe or wedge induced edgetone in a single free shear layer are found to be somewhat similar to those of the slit jet-wedge edgetone phenomenon. In any stage of operation, the edgetone frequency is directly proportional to the shear layer characteristic velocity scale U_e and nearly inversely to the lip-wedge distance h .

Detailed data pointed out some differences with published jet edgetone data; these differences are summarized below.

The free shear layer tone phenomenon does not appear to involve hysteresis in the frequency jumps between stages, as is observed in the jet edgetone case. The relative amplitudes of the two frequency modes (i.e. stages) around the inter-stage jumps were found to be independent of whether the controlling parameter viz. the lip-wedge distance h or the characteristic velocity scale U_e (thus also the length scale of the mean velocity profile) was increased or decreased. During a transition, the phenomenon was found to occur only in one mode at a time while randomly flipping

between the two modes. Single realizations of the tone flow frequency spectrum showed peak at one or the other of the two modes while a large ensemble average of the spectrum showed peaks corresponding to both modes. Our observation thus contrasts that in a jet edgetone where simultaneous existence of two modes (stages) has been reported. In these zones, as the parameter h or U_e was being varied, the amplitude of one component progressively decreased while the other increased. Present data show evidence of the existence of a minimum lip-wedge distance $h_{\min}$ for the edgetone to occur at a constant U_e .

In any stage of operation, the nondimensional frequency St_h is not found to remain constant as is the case in jet-wedge edgetone; St_h increased linearly with h . The shear layer data for any combination of h and U_e have been shown to fall on the same smooth curves in each stage on a St_h (or St_{θ_e}) vs. h/θ_e plot; thus permitting prediction of shear layer tone frequency for each choice of h , U_e , flow configuration (geometry) and initial condition (e.g. θ_e). These data confirm that θ_e , along with h , is an important length scale of the shear layer tone phenomenon and that this phenomenon is dependent also on the initial condition.

The occurrence of the subharmonic frequency in edgetone has not been reported previously even in acoustic measurements. Of course, occurrence of subharmonic frequency in the shear layer tone is well explained by the phenomenon of vortex pairing, which has been the subject of extensive, recent research. It appears that in the presence of strong feedback the vortex pairing, which otherwise occurs randomly in space and time, is organized and somewhat accentuated, thus giving an identifiable spectral peak in the frequency spectrum of the shear layer tone induced velocity signal. We have separately shown that under controlled excitation,

intense vortex pairing can be induced at fixed locations in space at exactly equal intervals in a circular air jet (Hussain and Zaman 1975, Zaman and Hussain 1977). Since flow visualization (Rockwell 1972) confirm occurrence of vortex pairing in plane jets, it is likely that in the jet edgetone case also the subharmonic frequency would occur but has not been reported in any study.

There is no clear evidence of a maximum lip-wedge distance for the shear layer tone to occur. The spectral components (including the subharmonics) gradually decrease in amplitude with increasing h before they are submerged by the evolving broadband turbulence.

The phase velocity and wavelength appear to be independent of the stage but increase monotonically with increasing h at each stage. Thus, when h is being increased at a fixed U_e , the wavelength and phase velocity will jump down to lower values at the start of the next stage. The phase velocity variation with increasing h in each stage suggests that the feedback from the wedge to the lip is hydrodynamic rather than acoustic.

The shear layer tone induced velocity fundamental amplitude and phase profiles show close agreement with the linear spatial instability theory of Michalke (1965). The difference between data and theory can be attributed to the differences in velocity profile and effects of nonparallel flow, free-stream turbulence, nonlinear disturbance amplitude, viscosity etc. The trend of variation of the tone eigenvalues i.e. the wavenumber and the phase velocity with the shear layer tone Strouhal number agrees well with the spatial stability theory; agreement with the data will be improved when the nonparallel effect is included in the spatial theory.

The relationship between the lip-wedge distance h and the wavelength λ is not found to satisfy the Brown-Curle equation $h = (J + \frac{1}{4})\lambda$ which is confirmed by many jet-wedge investigators. For the first two stages, we found the approximate relation to be $h \approx (J + C_1)\lambda$, λ decreasing slightly with increasing frequency; the parameter C_1 varies somewhat from stage to stage and within each stage; it is about 0.5.

From our data it is apparent that instability of the free shear layer, and the lip-wedge distance must be the key factors to produce its tone. The initial velocity profile and thus its characteristic length scale like initial momentum or vorticity thickness will affect its instability. The instability of the free shear layer is the pre-condition for edgetone; the wedge has no influence on the shear layer instability, other than to provide positive feedback to the sensitive point i.e. the lip and organize the otherwise randomly occurring instability, nonlinear saturation and vortex roll-up. In the absence of any controlled excitation or stable feedback like the edgetone, instability of the free shear layer will be randomly triggered by the ambient random disturbance; thus the frequency of the unstable mode will have a jitter and the location of roll-up of the shear layer will also change randomly. A particular mode finds stable amplification through the tone feedback when the corresponding most unstable wavelength matches appropriately with the lip-wedge distance or stated another way, when the shear layer instability induced disturbance at the wedge arrives at the lip at the correct phase to provide positive feedback and sustain the instability.

It appears that the nonparallel aspect of the shear layer instability is not the central factor in edgetone behavior. The role of instability in the shear layer tone is currently being further investigated in our laboratory.

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f (hz.)	Stage of Operation	Lip-Wedge distance h(cm)	$\alpha_r = \frac{\Delta\phi}{\Delta x} \left(\frac{\text{deg.}}{\text{cm}} \right)$	$\frac{v}{U_e} \frac{c}{U_e}$	h/ λ	$2\pi\theta_e/\lambda$
3100	I	1.138	-492	.610	1.56	.116
	II	1.750	-494	.607	2.40	.117
3300	I	1.041	-544	.589	1.57	.128
	II	1.598	-546	.586	2.42	.129
3500	I	0.914	-637	.531	1.62	.150
	II	1.440	-640	.531	2.55	.150
3700	I	0.813	-719	.498	1.62	.169
	II	1.334	-711	.503	2.64	.167

Table 1. Phase variation data for Stages I and II at $U_e = 37.2$ m/sec

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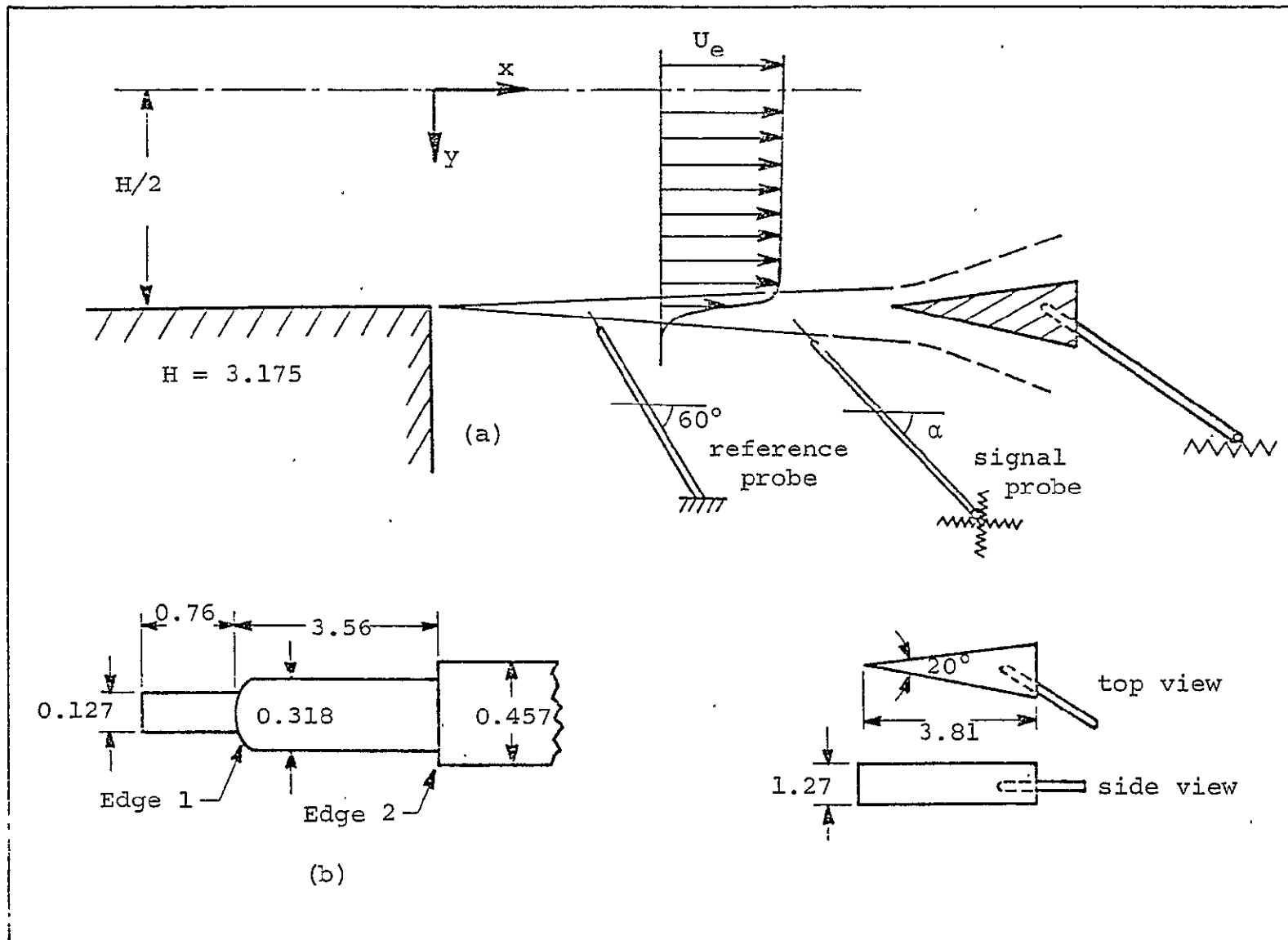


Fig. 1 (a) Schematic of the free shear layer, wedge and hot-wire probe arrangement; (b) hot-wire probe tip details; (c) wedge details. Dimensions are in cm.

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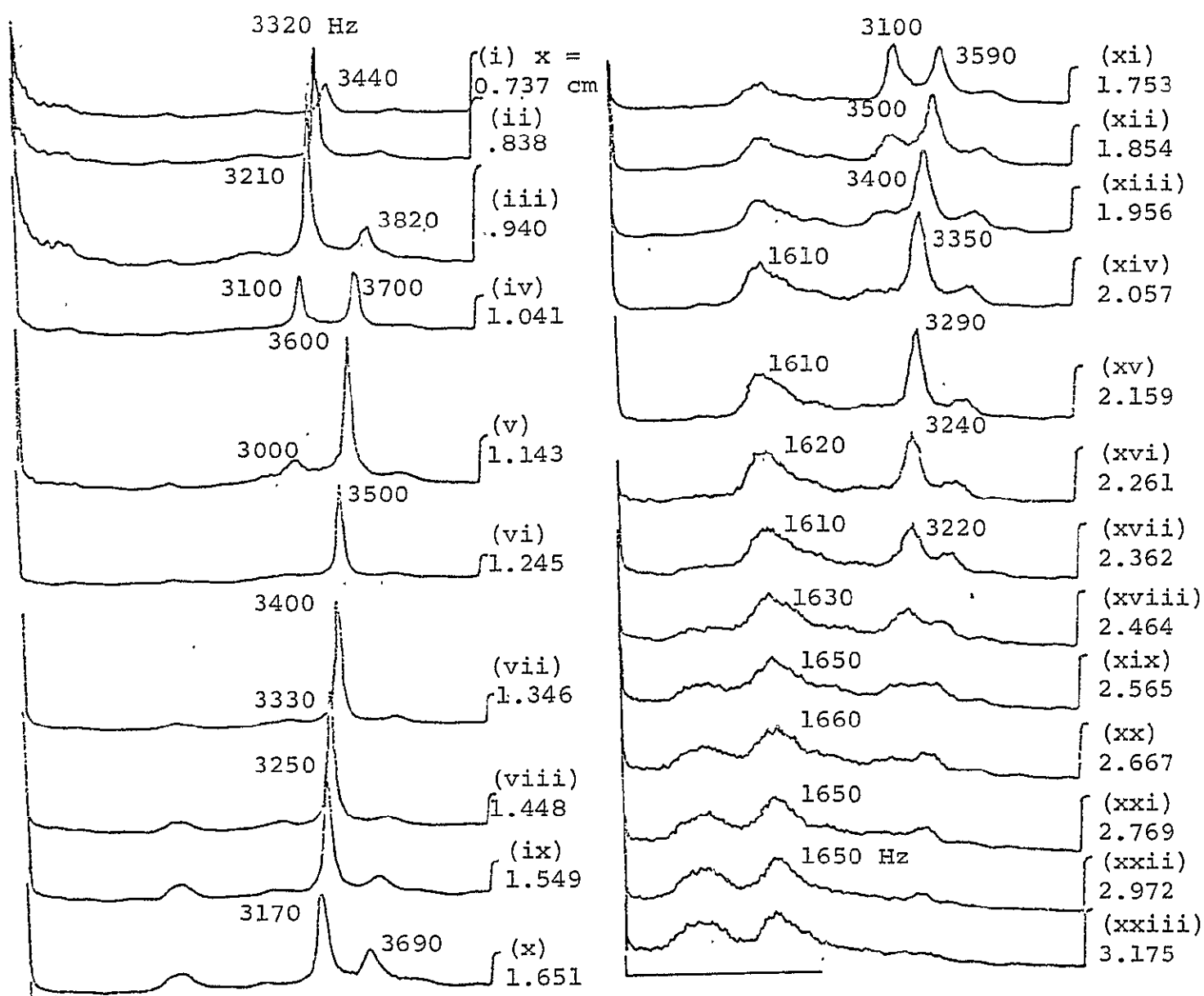


Fig. 2 Longitudinal one-dimensional velocity fluctuation spectrum $S_u(f)$ from the hot-wire probe placed at different axial locations x in the plane free shear layer; $U_e = 37.2$ m/sec. Probe placed at the y -location where $U/U_e \approx 0.95$. Plots are on linear-linear scales; abscissa range for all the figures is 0-5 kHz. Figs. (vi) - (xxiii) have identical vertical scale. With respect to this, the vertical scales for Figs. (i) - (iii) are magnified by a factor of 10 and those for Figs. (iv) - (v) by $10^{1/2}$.

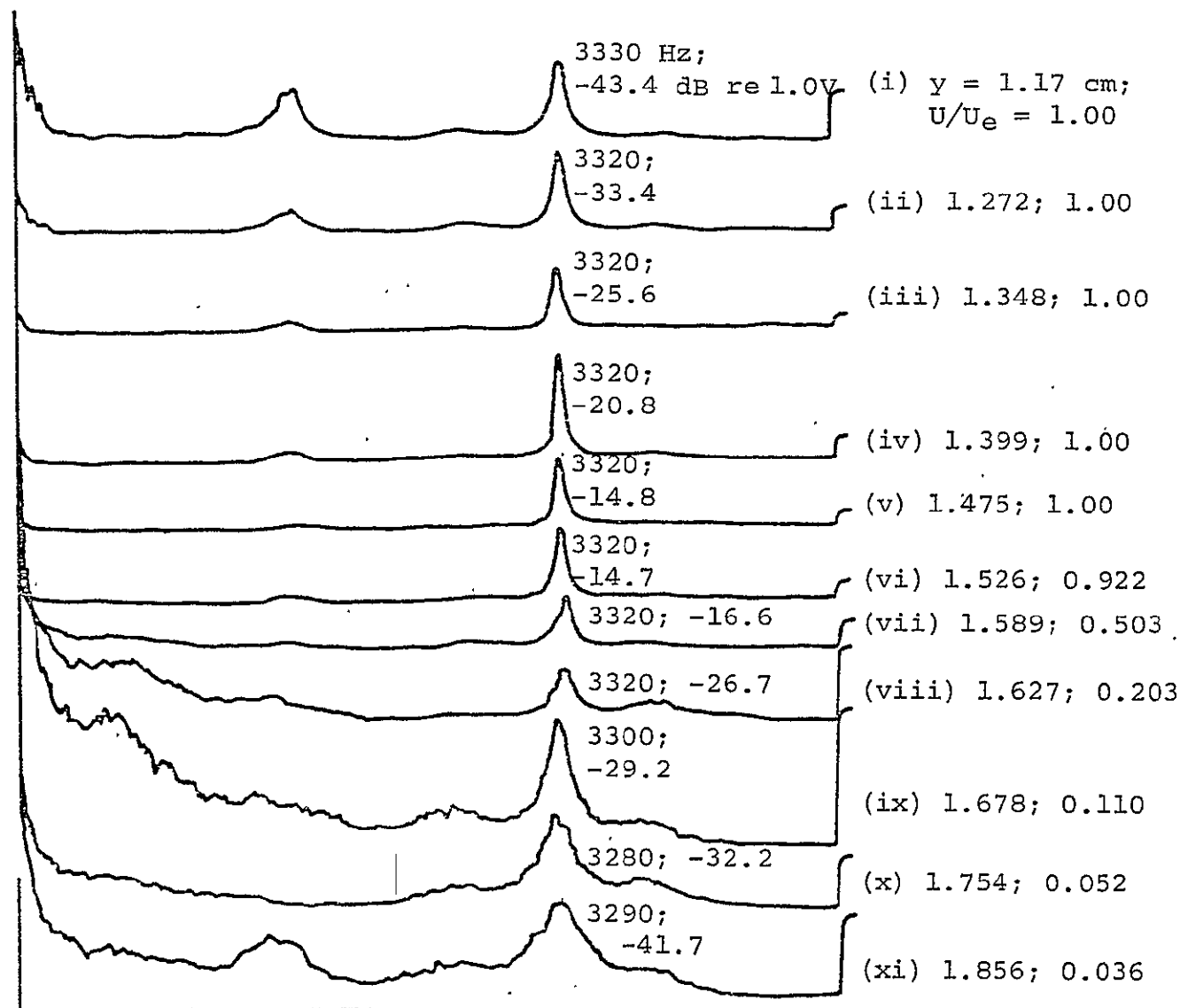


Fig. 3 Spectra $S_u(f)$ of velocity signal from the hot-wire placed at different transverse locations in the plane free shear layer at $x = 1.448$ cm; $U_e = 37.2$ m/sec. Plots are on linear-linear scales with the abscissa range 0-5 kHz and with arbitrary scales for the ordinates. Transverse location in cm and mean velocity U/U_e are shown on the right hand side of each spectrum plot.

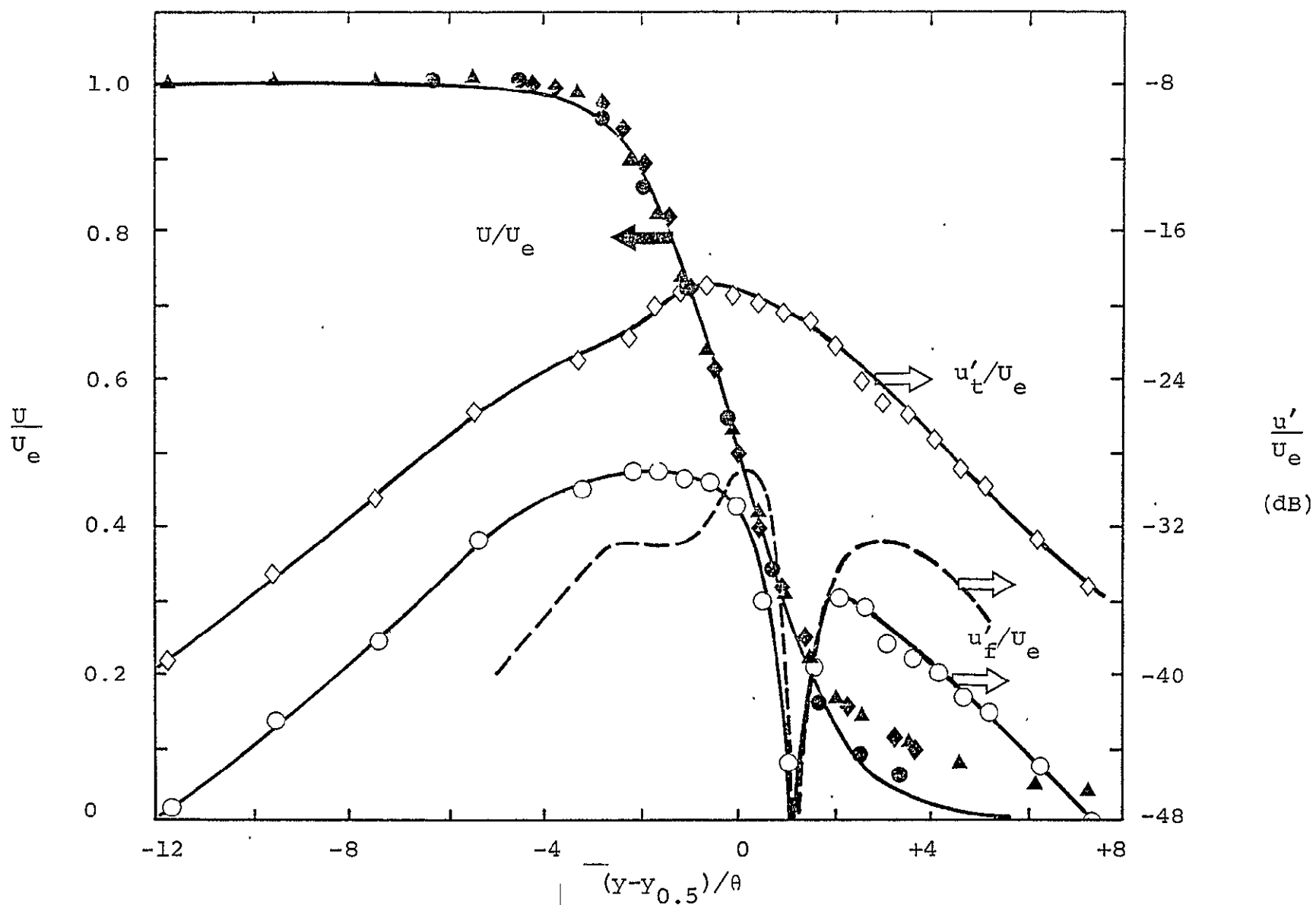


Fig. 4 Variation of the longitudinal mean velocity, total turbulence intensity and the shear layer tone fundamental amplitude (rms) as functions of normalized transverse distance from the half-mean velocity point for the plane free shear layer at $U_e = 37.2$ m/sec. Mean velocity at: Δ , $x = 0.25$ cm; $\circ$, $x = 1.35$ cm; $\diamond$, $x = 3.18$ cm; solid line through these data is the profile $U/U_e = 0.5 - 0.5 \tanh((y-y_{0.5})/20)$. - - measured total turbulence intensity (u'_t/U_e) at $x = 1.35$ cm. Shear layer tone fundamental amplitude (u'_f/U_e) at $x = 1.35$ cm: - - measured u'_f/U_e —, spatial stability theory (Michalke 1965).

f
(kHz)

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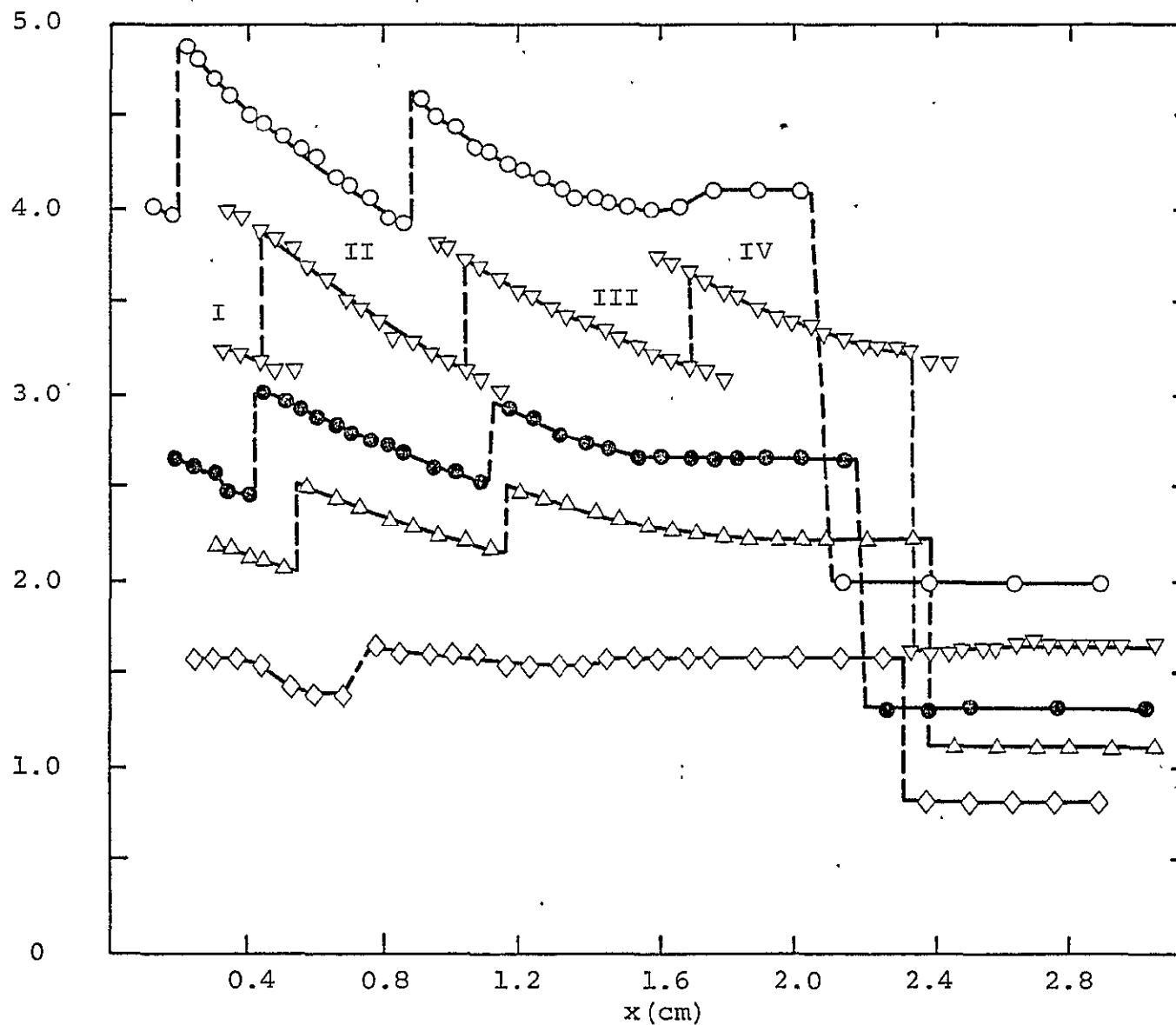


Fig. 5 Axial variation of the probe induced instability frequency of the plane free shear layer at different exit speeds U_e . $\circ$, U_e (m/sec) = 43.3; ∇ , 37.2; $\circ$, 32.0; Δ , 28.7; $\diamond$, 21.6. For the $U_e = 37.2$ m/sec the stages of the shear layer tone are indicated.

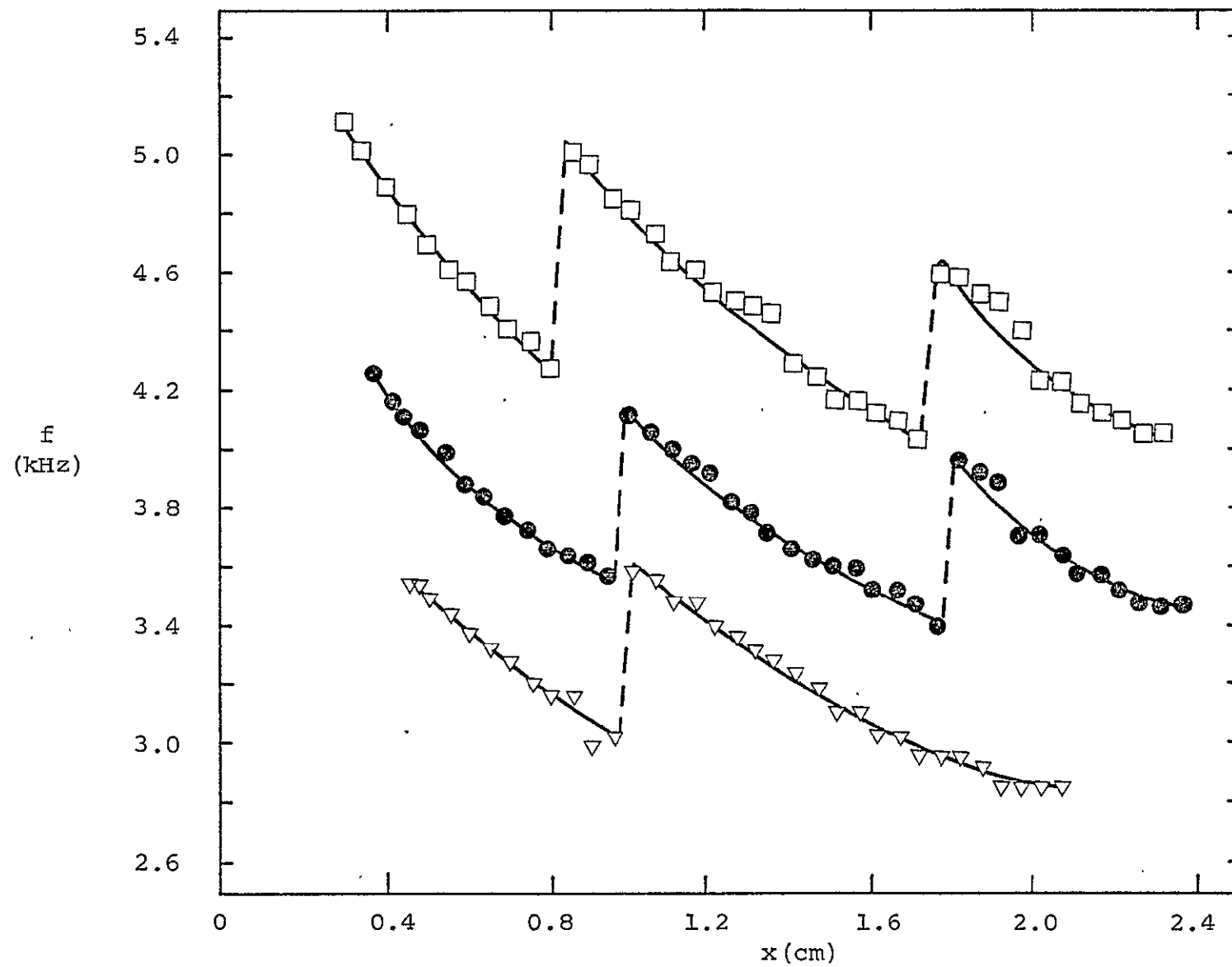


Fig. 6 Axial variation of the probe induced instability frequency for the axisymmetric free shear layer at different exit speeds U_e . $\square$, U_e (m/sec) = 46.0; $\circ$, 40.2; ∇ , 35.7.

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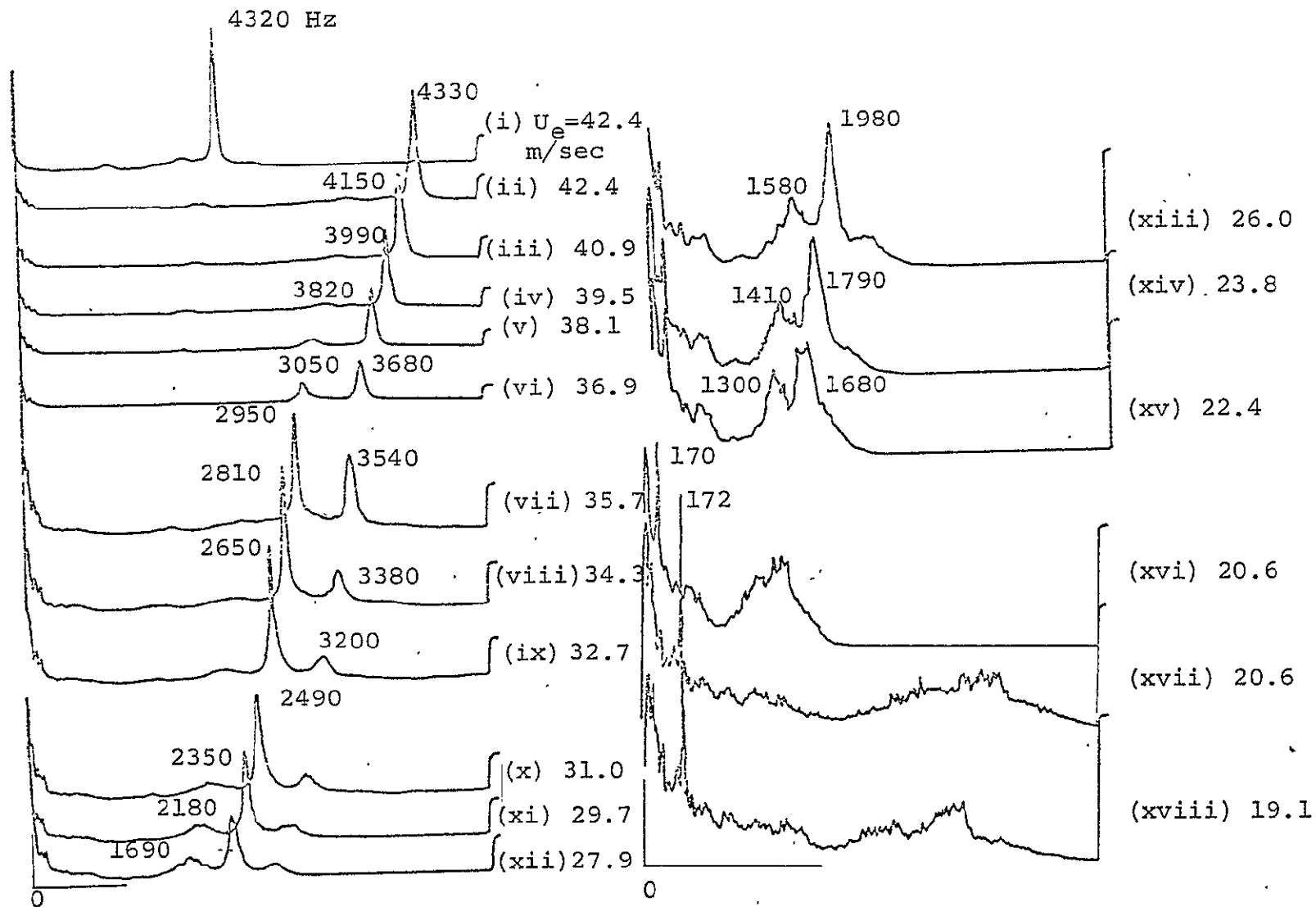


Fig. 6a Spectra $S_u(f)$ of the velocity signal in the plane free shear layer at different U_e . Hot-wire was placed at $x = 1.016$ cm while its transverse location was adjusted to keep $U/U_e \approx 0.95$. Plots are on linear-linear scales. Abscissa for (i) is 0-10 kHz; for (xvii) and (xviii) it is 0-2 kHz and for the rest of the figures it is 0-5 kHz. Vertical scales for the plots are arbitrary.

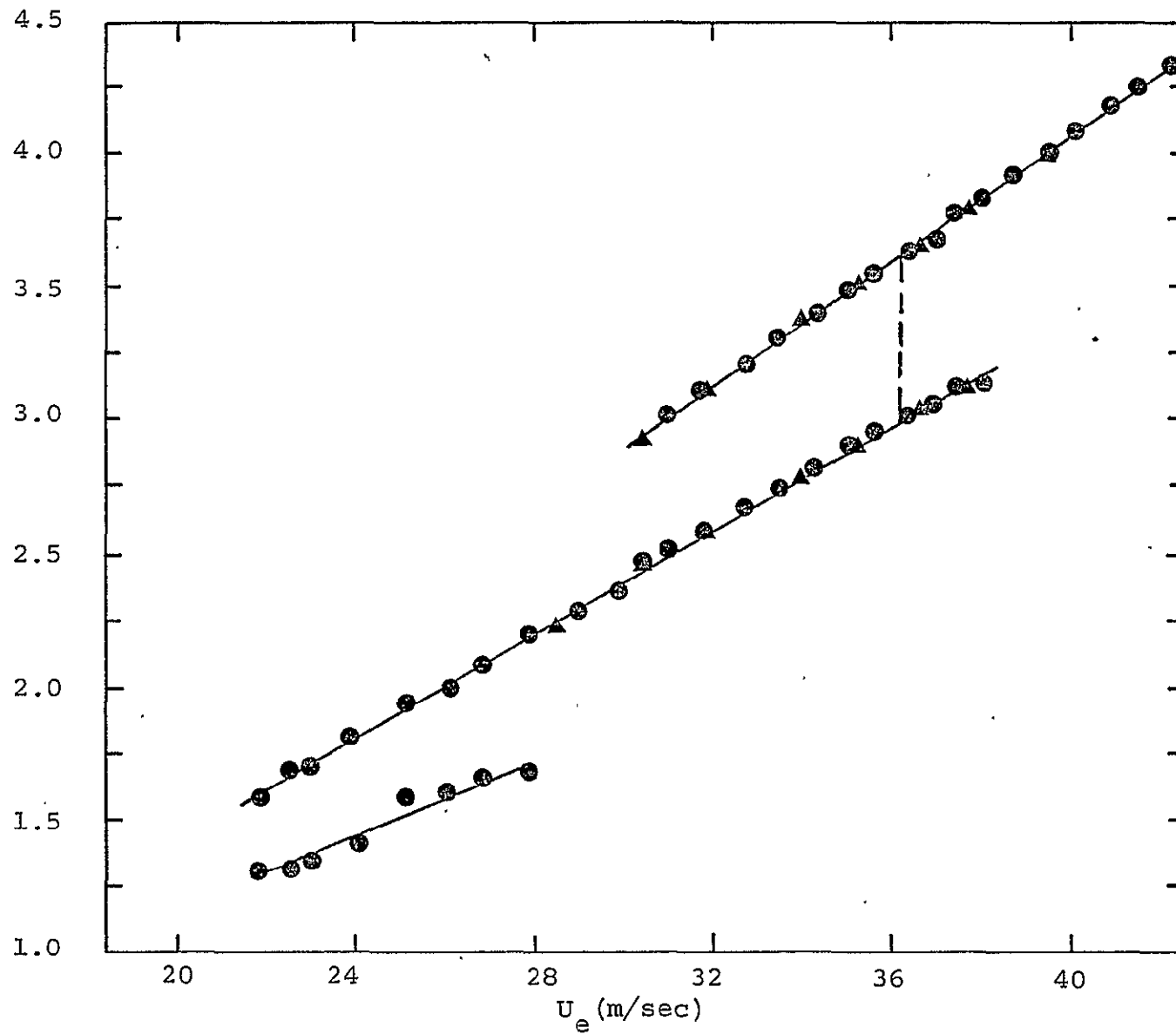


Fig. 8 Variation of the plane free shear layer tone frequency with exit mean speed U_e , corresponding to the spectral peaks in figure 7; circular data points for increasing U_e and triangular data points for decreasing U_e .

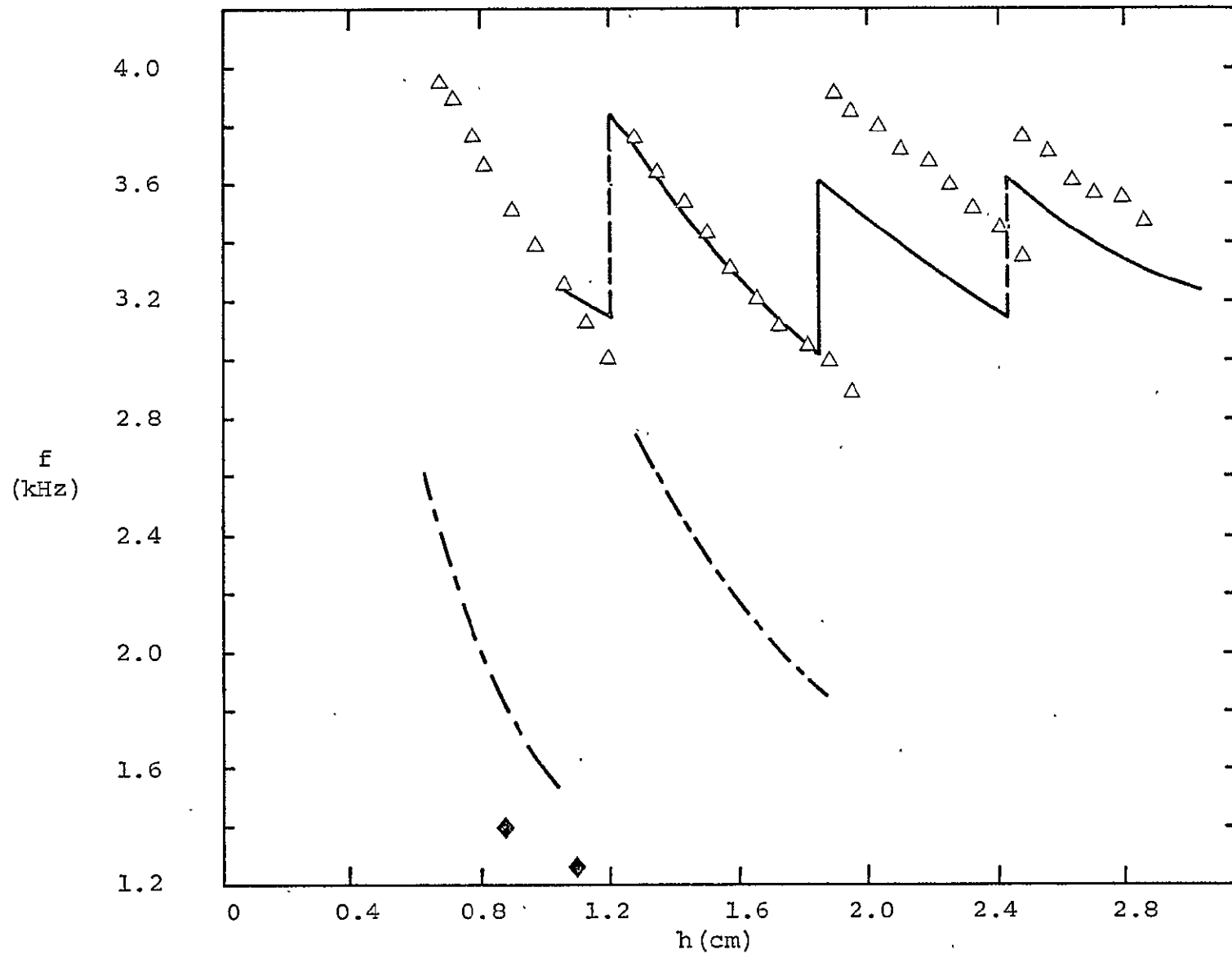


Fig. 9 Variation of the plane free shear layer tone frequency with the axial distance h of the wedge; $U_e = 37.2$ m/sec. The solid lines represent data obtained with the probe only (figure 5), the probe distance having been corrected to represent the distance from the lip to edge 1 of the probe (figure 1b). — — —, eqn. (1); , second stage data from Sarohia (1976).

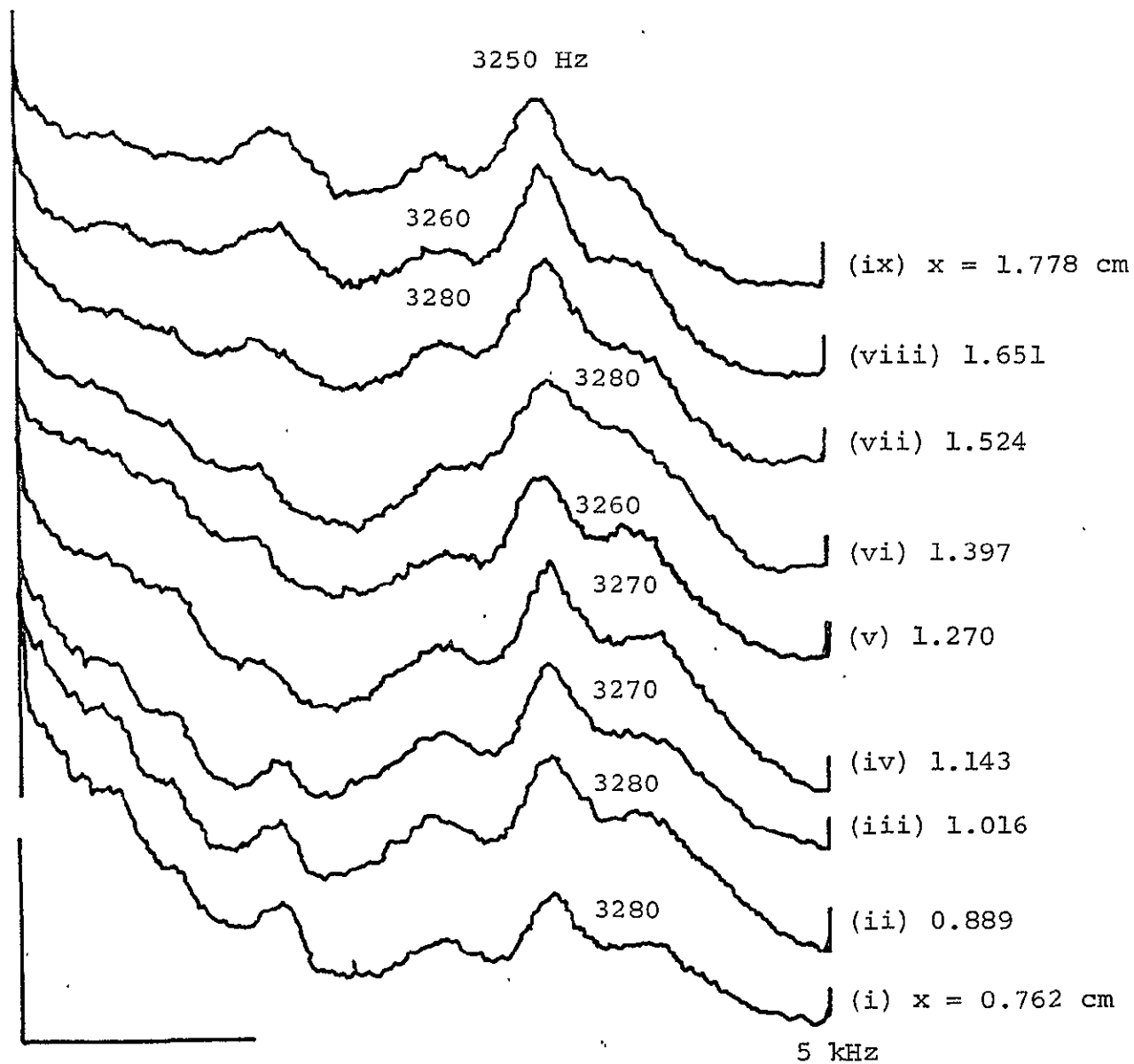


Fig. 10 Spectra $S_u(f)$ of the velocity signal at different axial locations of the hot-wire probe in the plane free shear layer; $U_e = 37.2$ cm. Probe axis makes an angle of 60° with the jet axis and transverse location of hot-wire at each x adjusted to keep $U/U_e = 0.10$. Plots are on log-linear scales; abscissa range is 0-5 kHz and ordinates are arbitrary.

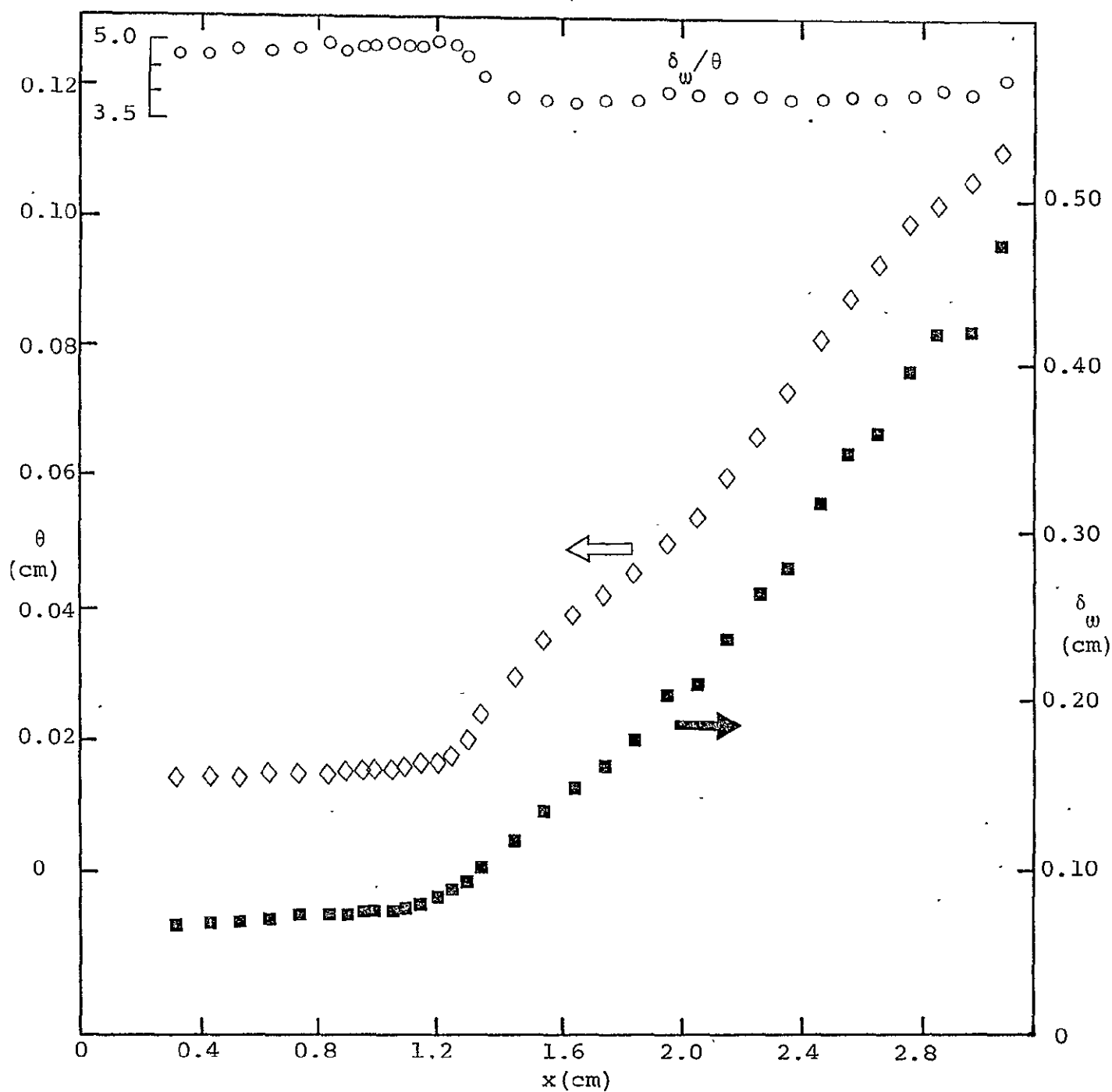


Fig. 11 Variations of the momentum thickness ($\diamond$), the vorticity thickness ($\blacksquare$) and the ratio δ_w/θ (O) of the plane free shear layer with axial distance; $U_e = 37.2$ m/sec.

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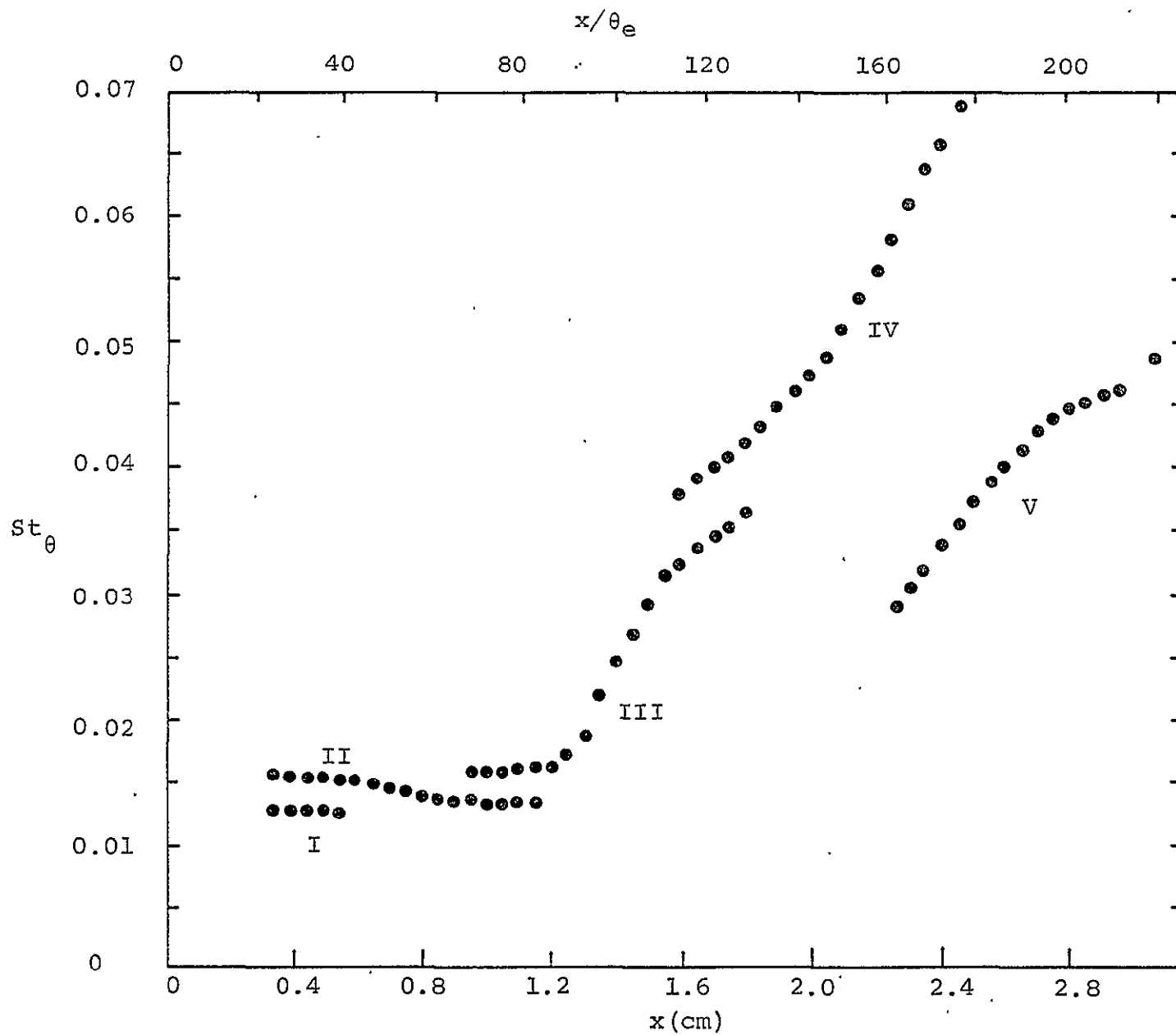


Fig. 12a Strouhal number St_θ (based on local θ) vs. axial distance for the plane free shear layer at $U_e = 37.2$ m/sec. The stages indicated correspond to those in figure 5.

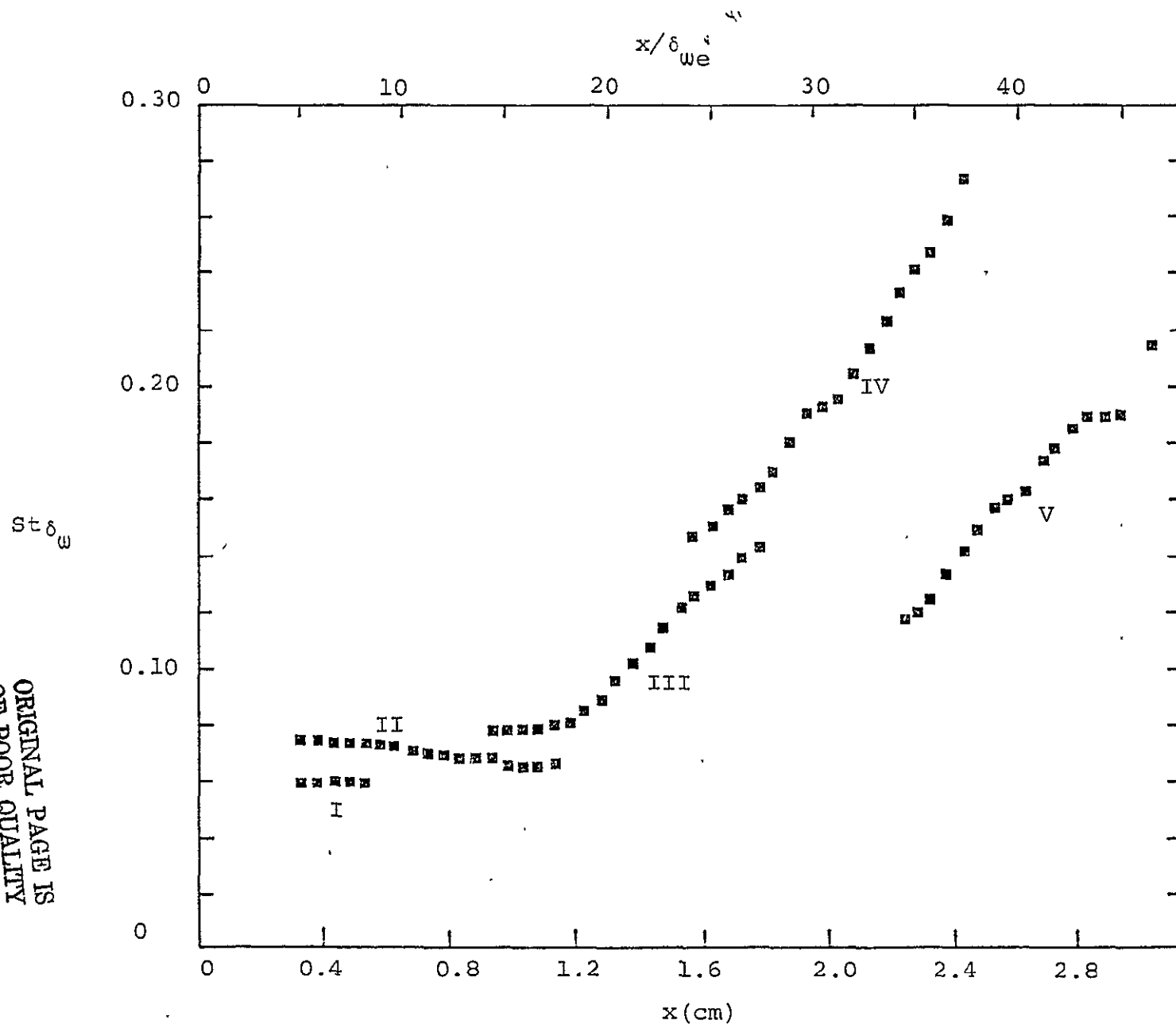


Fig. 12b Strouhal number $St\delta_w$ (based on local vorticity thickness) vs axial distance for the plane free shear layer at $U_e = 37.2$ m/sec. The stages indicated correspond to those in figure 5.

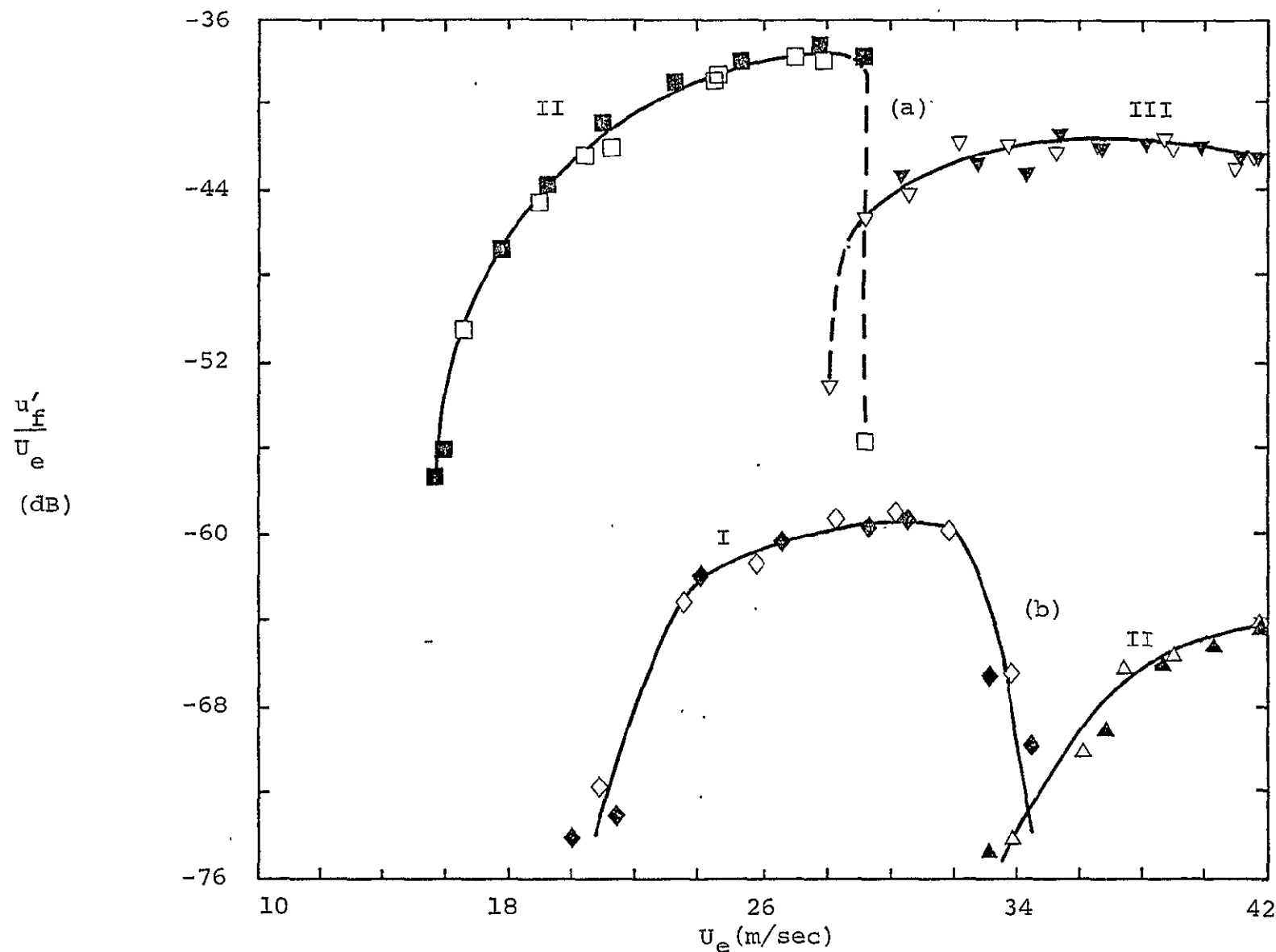


Fig. 13 Variation of the rms amplitude of the plane free shear layer tone velocity spectral component with U_e ; (a), data obtained with wedge at $h = 1.83$ cm; probe placed at $x = 1$ cm and $U/U_e \approx 0.95$ point; (b), data with $h = 1.22$ cm; probe placed at $x = 0.63$ cm and $U/U_e \approx 0.95$ point. Solid data points were obtained while U_e was being decreased and the open ones while U_e was being increased.

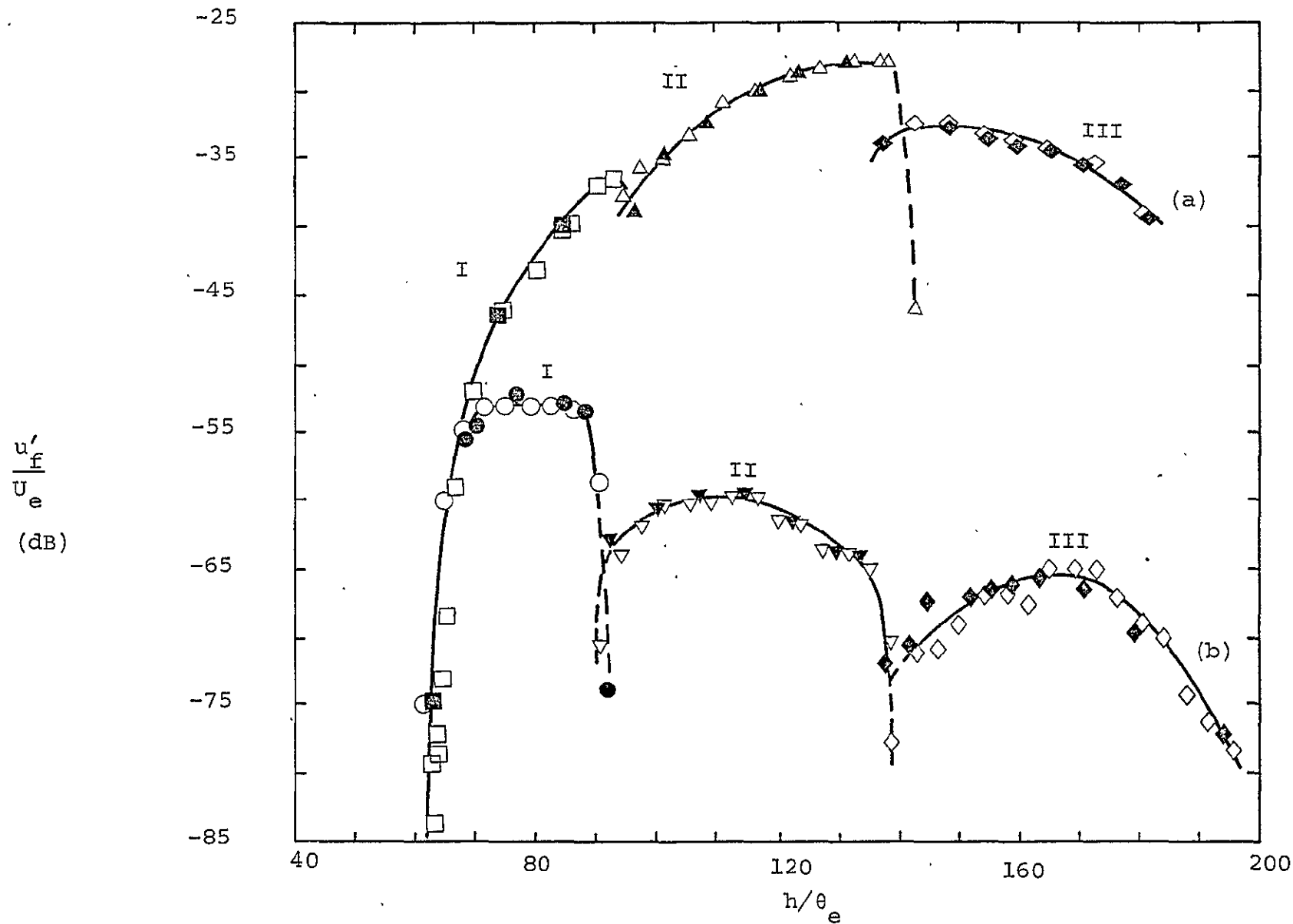


Fig. 14 Variation of the rms amplitude of the palne free shear layer tone velocity spectral component with axial distance h of the wedge; (a), the probe moved with the wedge. (b), the probe fixed at a point ($x = 0.25$ cm and $U/U_e \approx 0.95$) in the flow. The solid data points were obtained while h was being decreased and the open ones while h was being increased.

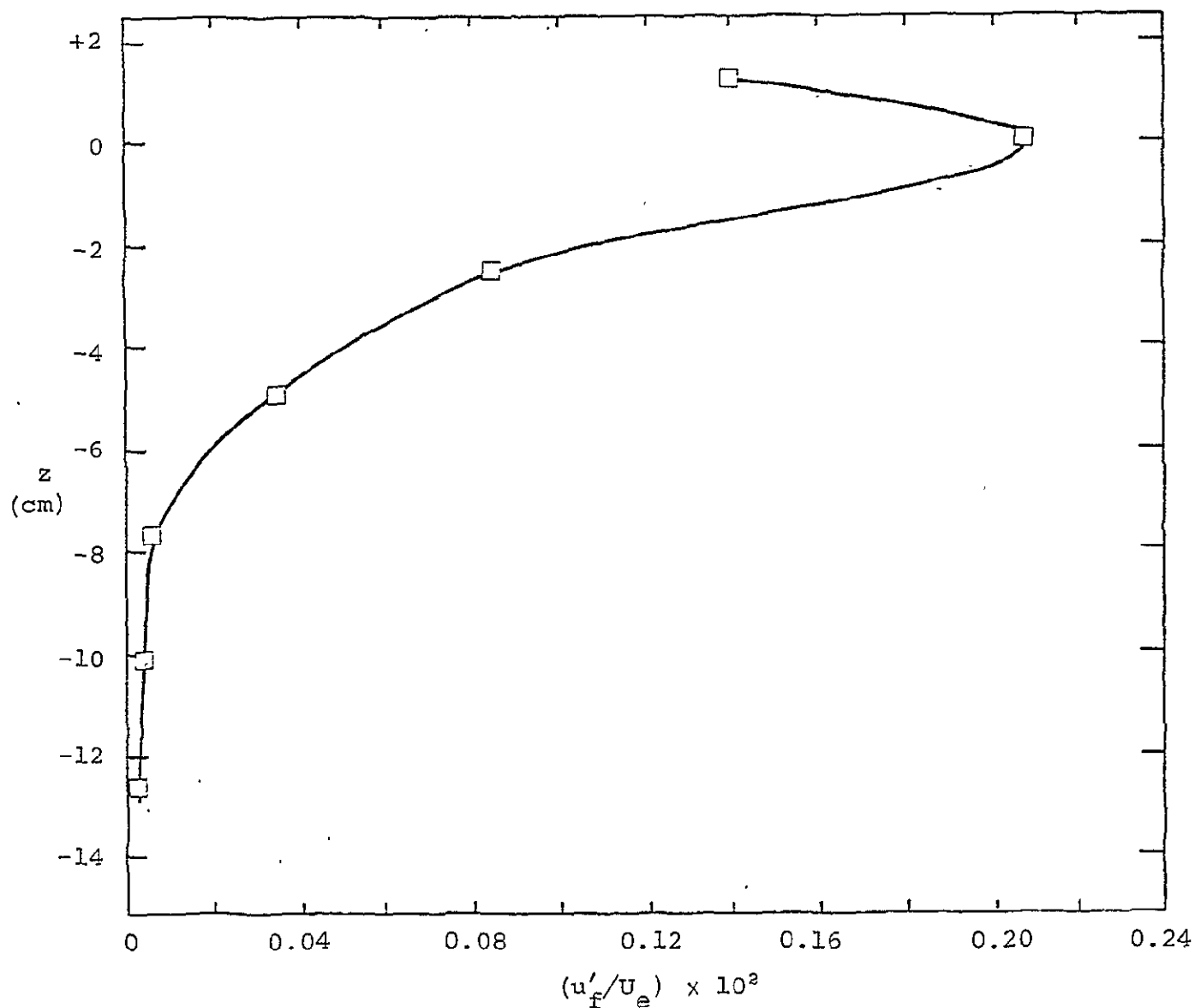


Fig. 15 Variation of the rms amplitude of the shear layer tone velocity spectral component with spanwise distance relative to the wedge; $U_e = 37.2$ m/sec; h is such that $f = 3320$ Hz in stage II; probe traversed at constant x and y .

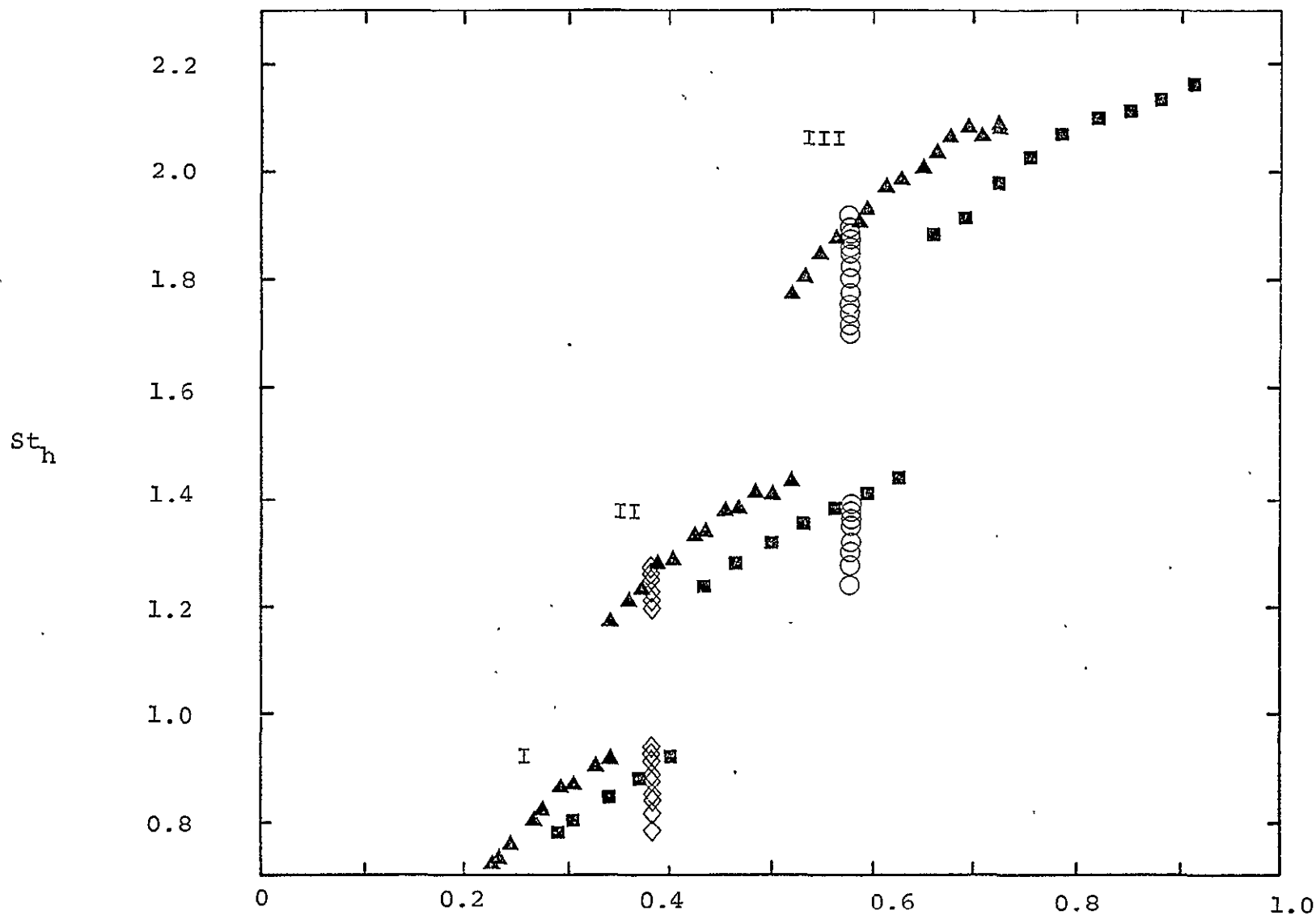


Fig. 16 Strouhal number St_h of the wedge induced plane free shear layer tone as a function of lip-wedge distance h ; Δ , variable h at $U_e = 43.3$ m/sec; $\square$, variable h at $U_e = 29.3$ m/sec; $\diamond$, variable U_e with $h = 1.22$ cm; $\circ$, variable U_e with $h = 1.83$ cm.

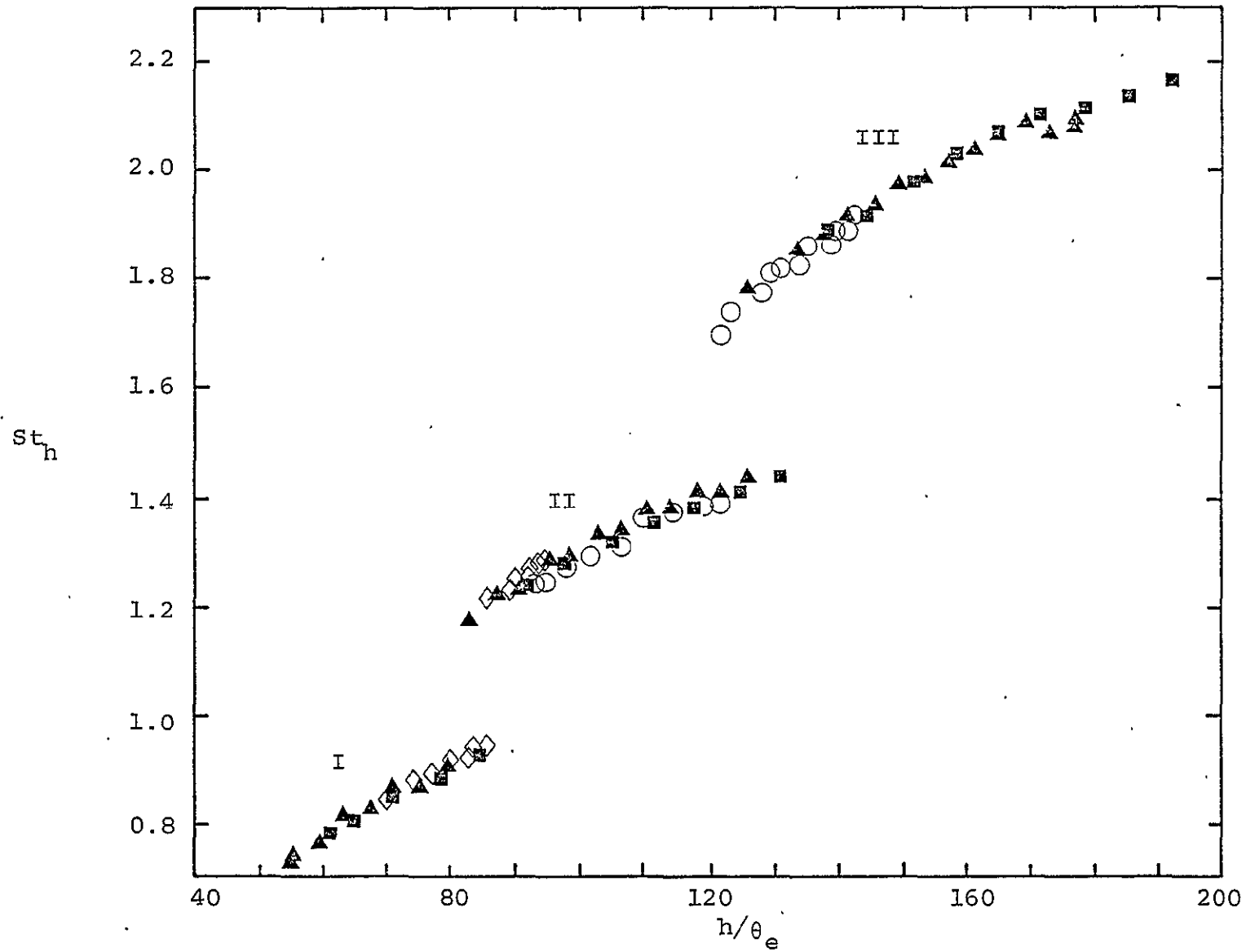


Fig. 17a Strouhal number St_h of the plane free shear layer tone as a function of h/θ_e for different stages. The four data symbols used represent the same four cases in figure 16.

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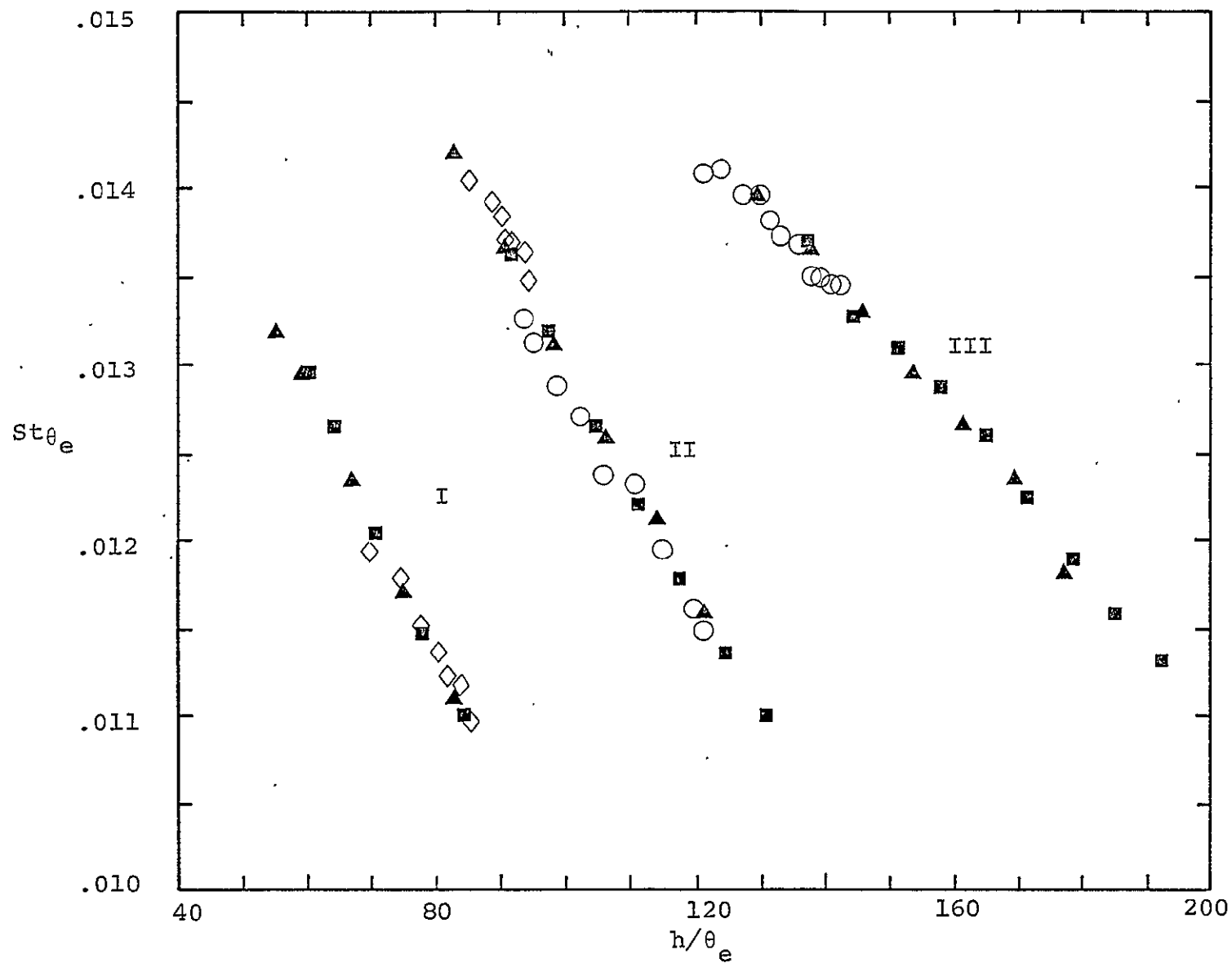


Fig. 17b St_{θ_e} as a function of h/θ_e for different stages. The four data symbols used represent the same four cases in figure 16.

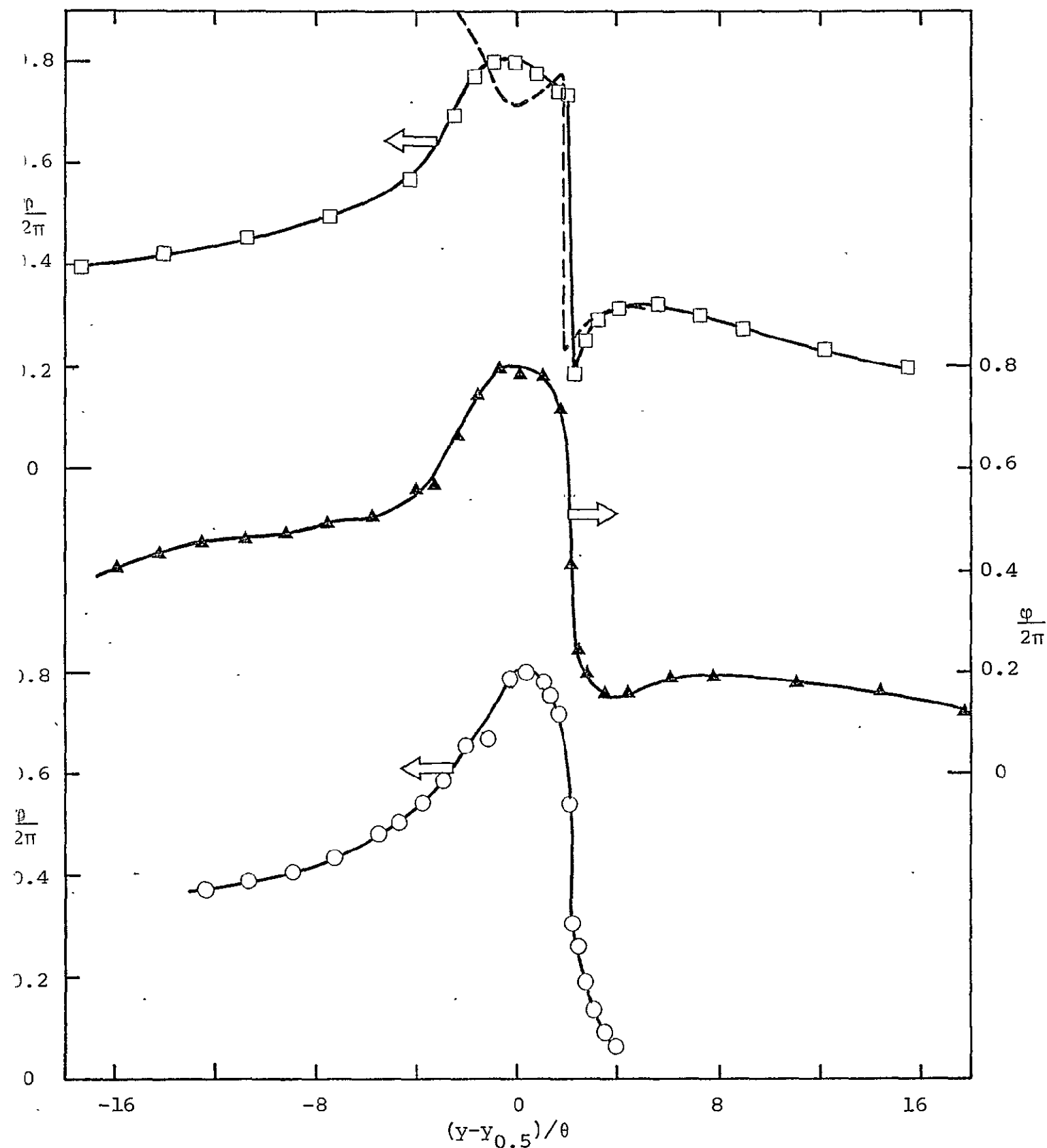


Fig. 18a Transverse phase variation of the shear layer tone fundamental for the plane free shear layer at $U_e = 37.2$ m/sec. Wedge at $h = 1.4$ cm producing tone at $f = 3500$ Hz (stage II). O, $x = 0.508$ cm; Δ , $x = 0.762$ cm; $\square$, $x = 1.016$ cm; — — —, spatial stability theory for $x = 1.016$ cm (Michalke 1965).

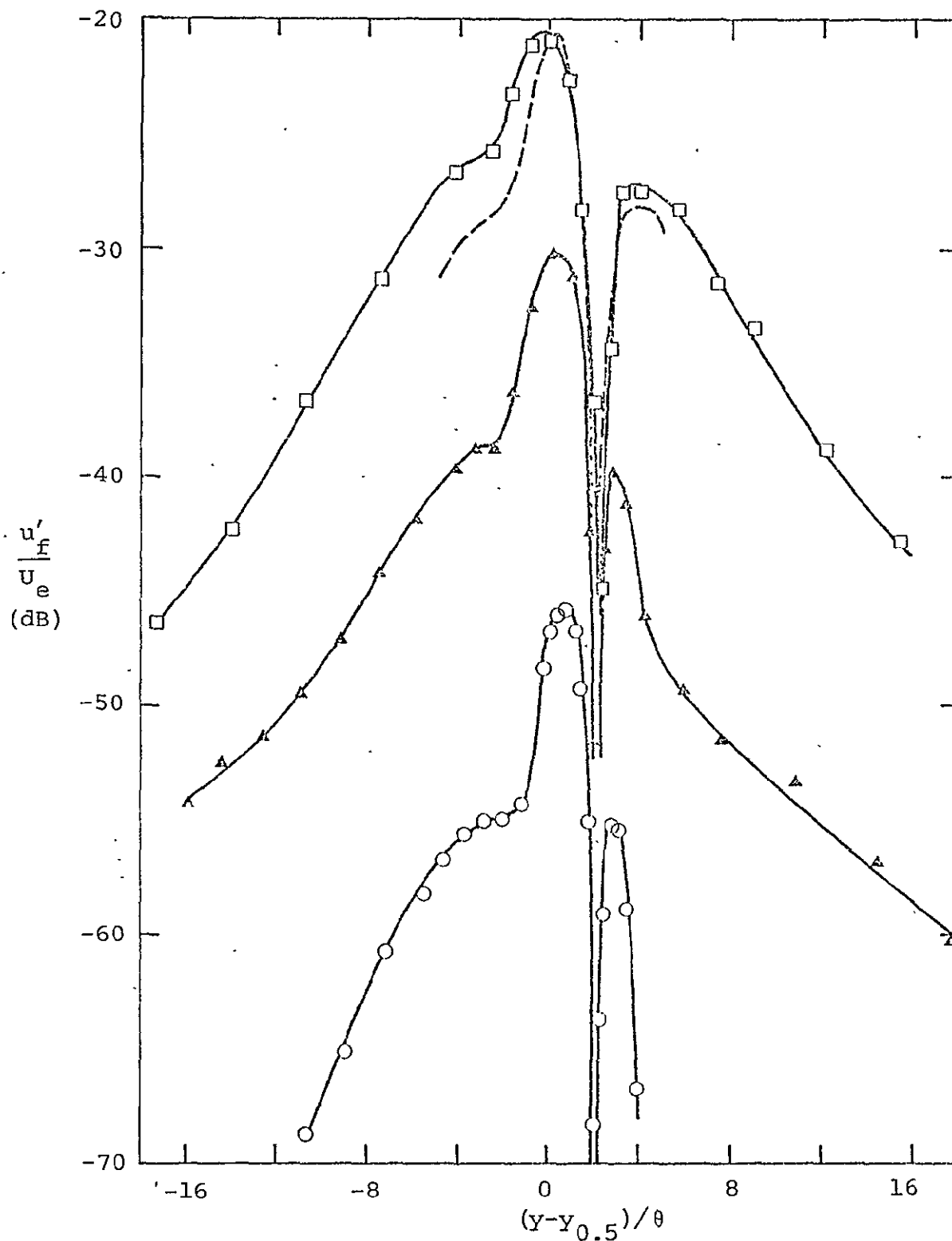


Fig. 16b Transverse amplitude (rms) variations of the shear layer tone fundamental corresponding to the three axial stations shown in figure 18a. The data symbols used represent the same cases in figure 18a. ---, spatial stability theory, for $x = 1.016$ cm, (Michalke 1965).

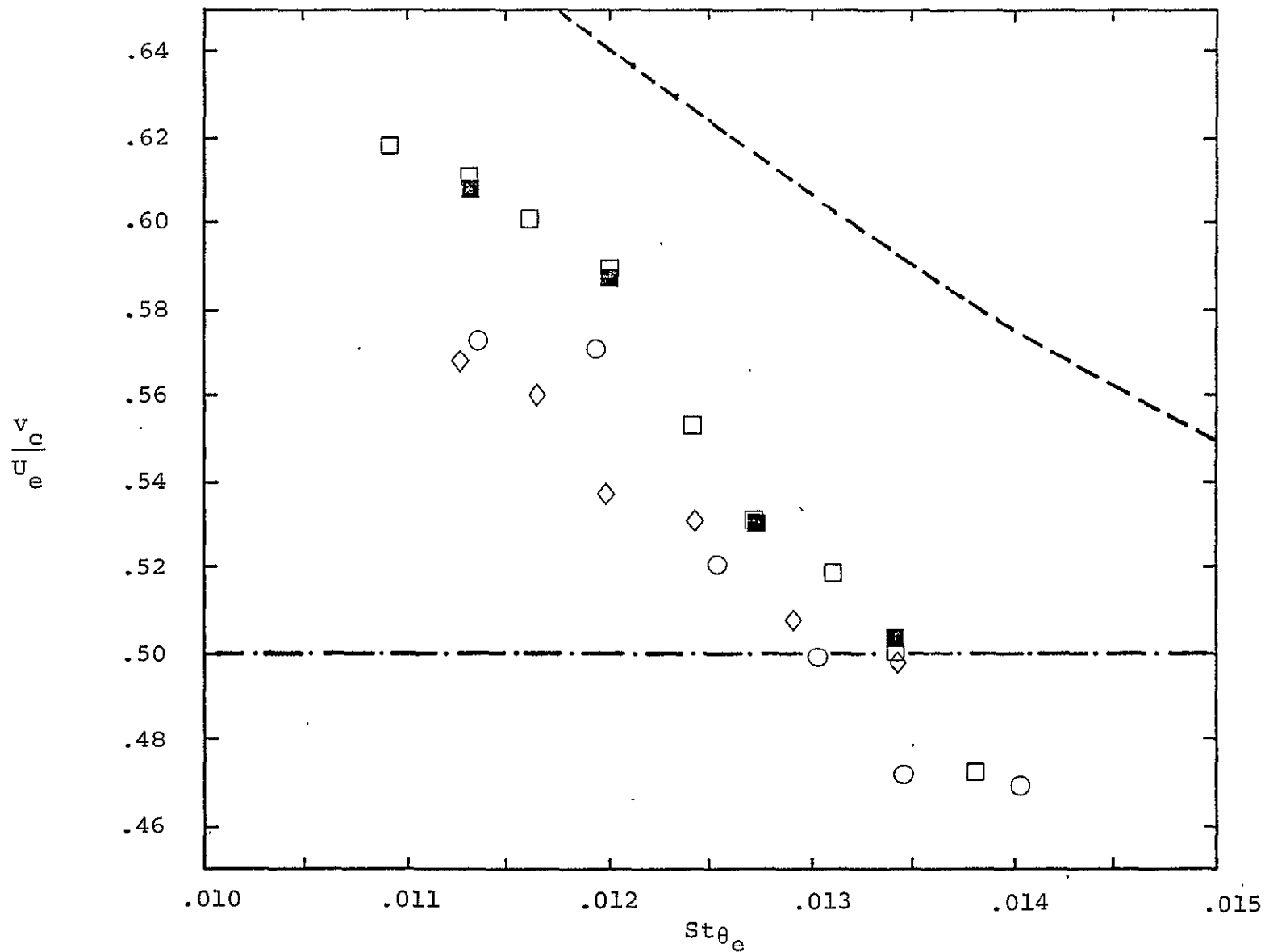


Fig. 19a Variation of the phase velocity v_c with the plane shear layer tone nondimensional frequency St_{θ_e} . All the data except the four represented by the solid squares were obtained with Stage I operation. $\diamond$, $U_e = 29.3$ m/sec; $\square$, $U_e = 37.2$ m/sec; $\blacksquare$, $U_e = 37.2$ m/sec (Stage II operation); $\circ$, $U_e = 43.3$ m/sec. ---, spatial theory (Michalke 1965);

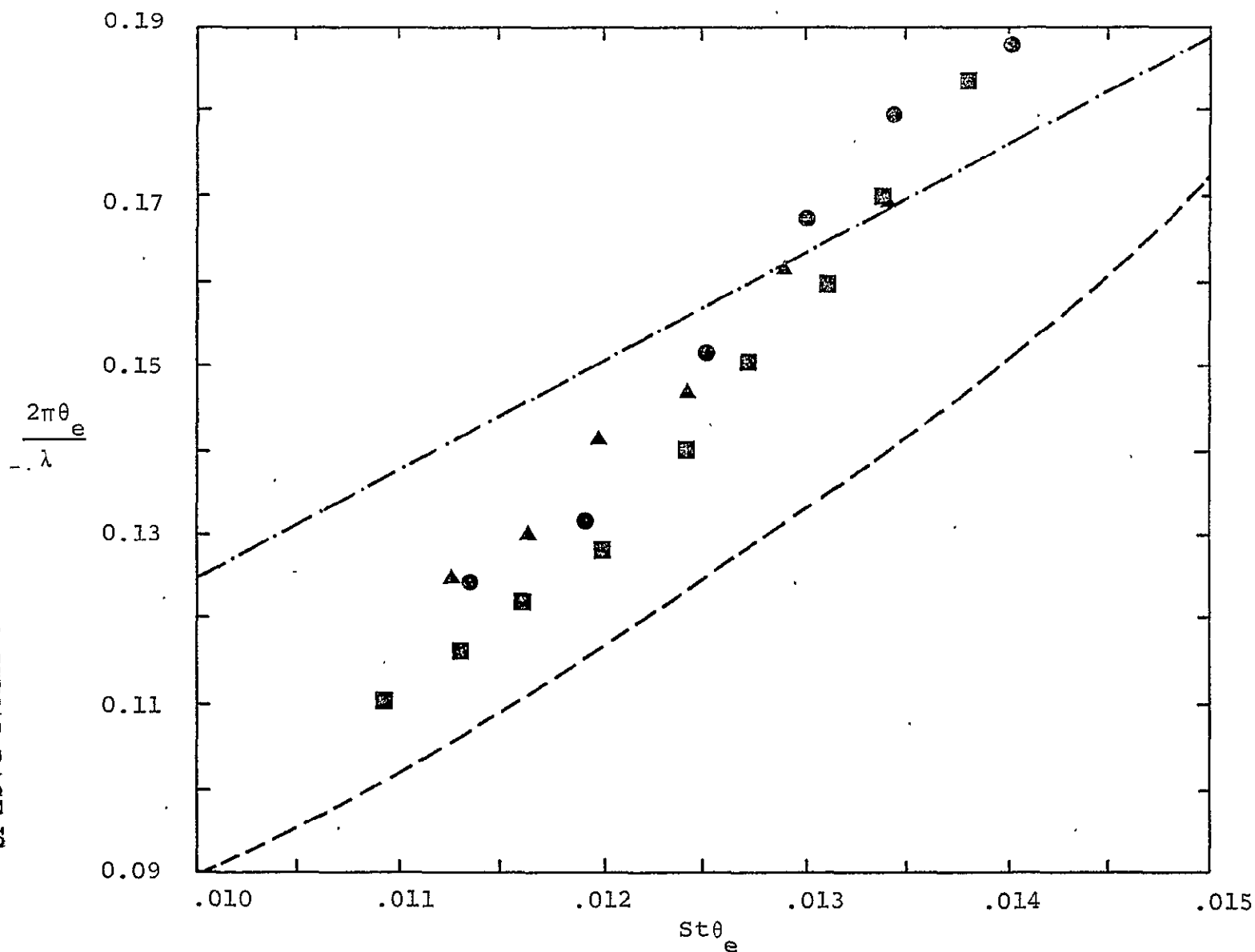


Fig. 19b Variation of the nondimensional wavenumber of the plane free shear layer tone as a function of $St\theta_e$ for stage I. $\circ$, $U_e = 29.3$ m/sec; $\triangle$, $U_e = 37.2$ m/sec; $\square$, $U_e = 43.3$ m/sec; — — —, spatial theory (Michalke 1965); — · —, temporal theory (Michalke 1965).

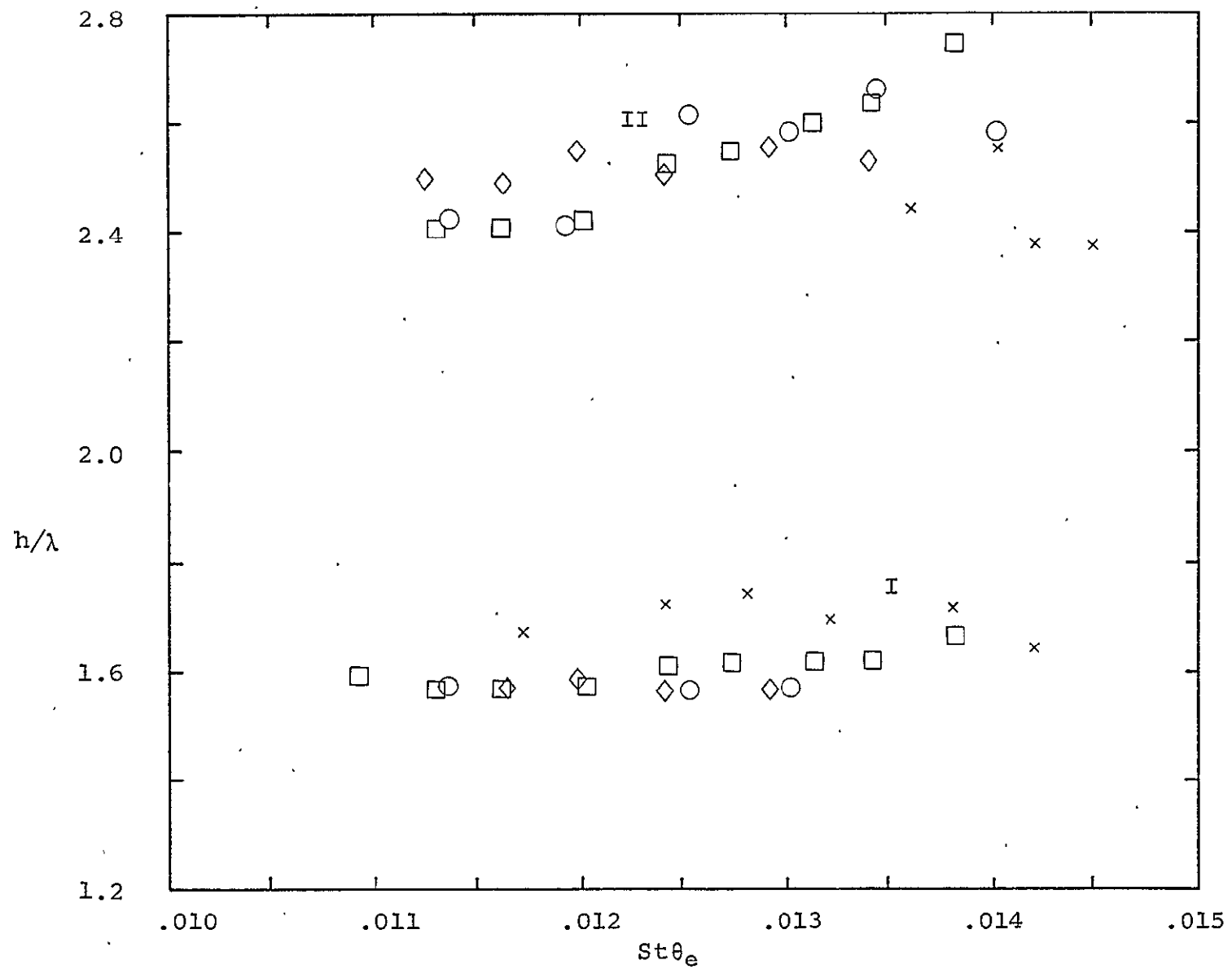


Fig. 20 Variation of the ratio h/λ with the shear layer tone frequency $St\theta_e$ for the first and second stages. $\diamond$, $U_e = 29.3$ m/sec; $\square$, $U_e = 37.2$ m/sec; $\circ$, $U_e = 43.3$ m/sec; $\times$, Sarohia (1976).

Appendix A

VORTEX PAIRING AND ORGANIZED STRUCTURES IN AXISYMMETRIC
JETS UNDER CONTROLLED EXCITATION

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ABSTRACT

The conditions most favorable for vortex pairing in the near field of a circular jet have been investigated through hot-wire measurements in two circular air jets subjected to controlled excitation. Two distinct modes of vortex pairing, inferred from the subharmonic spectral component of the u -signal, have been identified. The first mode is attributed to the exit shear layer instability which scales on the exit free shear layer width, and the second (jet) mode scales on the jet diameter. Strongest pairing occurs at $St_\theta = 0.011$ in the 'shear layer mode' and at $St_D = 0.85$ in the 'jet mode'. At relatively high St_D , the shear layer mode (at $St_\theta = 0.011$) was observed to involve successive stages of pairing; however, only one pairing could be identified in the jet mode even though St_θ varied over a wide range. The data indicate that the two modes of vortex pairing are independent and excitation at one of the modes is sufficient to induce vortex pairing in the near field irrespective of whether the excitation corresponds to the other mode or not.

NOMENCLATURE

x = axial distance downstream from the jet exit plane
 D = exit diameter
 δ = momentum thickness of efflux boundary layer measured at 0.3 cm upstream from the exit
 f_p = Frequency of controlled excitation producing sinusoidal surging at the exit
 U = longitudinal mean velocity
 u'_t = longitudinal total fluctuation intensity (rms)
 u'_f = rms amplitude in the u' signal at f_p
 $u'_f/2, u'_f/4, u'_f/8$ = rms amplitude in the u' signal at the successive subharmonic frequencies
 u'_{ec}/U_{ec} = relative exit excitation level

$$St_D = \frac{f_p D}{U_e}$$

$$St_\theta = \frac{f_p \theta}{U_e}$$

$$Re_D = \frac{U_e D}{\nu}$$

Subscripts

e = jet exit
 c = jet centerline

INTRODUCTION

The developing regions of free turbulent shear flows are dominated by large scale coherent structures

which appear to play the key role in observed near field gross features like entrainment, mixing and aerodynamic noise production [1-5]. It is reasonable to suspect that the large scale coherent structures of the developing region persist in the so-called self-preserving regions of these shear flows. Thus, it is likely that the coherent structure in a turbulent shear flow never truly achieves independence of the initial condition in a finite flow length, and that turbulence self-preservation, though a valid concept for the asymptotic far-field, may not be achievable in laboratory flows.

The evolution of the large scale structure in free shear flows appears to occur through interactions (like pairing) of large-scale vortical motions [1,2,5-8], an antiscascade phenomenon occurring simultaneously with the evolution of the small scale motions through vortex stretching. When the initial free shear layer is laminar, the initial vortical structure results from the (inviscid) instability and roll-up of the free shear layer, the initial size and spacing being determined by the most unstable eigenmode of the profile. It is possible that a free shear layer resulting from an initially turbulent boundary layer can also roll up into organized vortical structure which then evolve not unlike the initially laminar case.

The role of vortex pairing in mixing layer growth has been the subject of extensive recent studies. Winant and Browand [8] showed that any non-uniformity in strengths or spacing of two (or three) adjacent rolled up line vortices, formed in a water mixing layer, caused them to undergo successive stages of pairing to form progressively larger coherent structure downstream. They inferred that ingestion of non-turbulent fluid during the pairing process was the primary mechanism for entrainment and thus growth of the shear layer. Browand and Wiedman [9] has shown that significant Reynolds stress production is associated with the vortex pairing interaction process.

Browand and Laufer [1], from a flow visualization experiment in a circular water jet, hypothesized that the large scale structures just downstream of the potential core can be traced back to the upstream vortices whose generation depended on the exit shear layer instability. They observed difference in the statistical behavior (e.g. passage frequency, spatial coherence) between these initial rolled up vortices and the downstream large scale structures, and conjectured that independence of the large scale structure further downstream from the initial shear layer structure was achieved by successive stages of vortex pairing.

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Davies and Yule [10] in a summary of the Colloquium on organized turbulence structures held at the University of Southampton in 1974, described Yule's own findings of coherent structures in axisymmetric jets from flow visualization experiments. Observation within the first ten diameters revealed the existence of interacting and coalescing ring vortices, and the large scale organized structures downstream in the turbulent round jet 'differed fundamentally from the laminar ring vortices nearer the nozzle from which they developed'.

Crow and Champagne [11] observed the existence of orderly 'vortical puffs' in axisymmetric jets, in addition to the slender vortex rings formed near the exit due to exit shear layer instability and roll up. They destroyed the 'surface ripples' by tripping the exit boundary layer and studied the effect of controlled excitation on the 'puff mode'. They found that the 'preferred mode', i.e. the one producing maximum disturbance amplification downstream, occurred at $St_D = 0.30$. They also noticed pairing of the vortex puffs giving rise to a strong subharmonic structure when driven at twice the preferred mode, namely at $St_D = 0.60$.

The effect of acoustic excitation on the near flow structure of jets have been studied among others by Becker and Massaro [12], Rockwell [13], Vlasov and Ginevskiy [14] and the present authors [5]. Becker and Massaro [12] found that the Strouhal number (St_D) of the disturbance to which a given circular jet exit shear layer was most unstable varied approximately as the square root of the Reynolds number (Re_D). Rockwell [13] classified the plane jet flow under acoustic excitation into five regions depending on the ratio of excitation frequency (f_p) to the natural vortex roll-up frequency (f_N). He found that in two of these five regimes, the effect of excitation was very pronounced and clear vortex roll-up followed by coalescence phenomenon occurred. One of these two regimes corresponded to the case when the two frequencies matched and in the other the ratio between the two was about one third i.e., $f_p/f_N = 1/3$. Vlasov and Ginevskiy [14] observed large amplification of centerline turbulence intensity at $St_D = 0.5$ but its suppression relative to the non-excited case at $St_D = 2.75$.

As reported in ref. [5], we had noticed the occurrence of a stable vortex pairing phenomenon in circular jets at $St_D = 0.85$ for three different nozzles over a moderate range of Re_D , the exit shear layer thickness in that range varying appreciably. This led us to suspect that the observed pairing phenomenon was not a consequence of the initial shear layer instability mechanism.

The present study evolved as a result of an effort to define the ranges of characteristic jet flow parameters favoring strong vortex pairing and to understand the role of exit shear layer instability on the vortex pairing mechanism in the jet.

As we shall see, the vortex pairing observed at $St_D = 0.85$ seems to be associated with a distinct mode of instability of circular jets, and independent of the initial shear layer instability.

EXPERIMENTAL PROCEDURE

The experiments have been carried out in a circular air jet facility consisting of two settling chambers in sequence. Sinusoidal perturbations in the exit profile are introduced at controlled frequencies and amplitudes with the help of a loud-

speaker attached to the wall of the first chamber. The flow from the first settling chamber goes through a contraction and a diffuser into the second settling chamber before exiting through the nozzle into a large room with controlled temperature and humidity. The two settling chamber arrangement was introduced for eliminating any possible asymmetry introduced by the speaker. The exit mean and turbulence profiles were checked to be axisymmetric. The absence of any harmonic of the excitation frequency in the spectra of the exit velocity signal confirmed that the excitation was indeed pure tone (sinusoidal). The study was carried out with two nozzles (of Batchelor-shaw contour) of diameters 2.54 and 7.62 cms.

Probe traverses, with a traverse mechanism capable of movement in axial (x), transverse (y) and azimuthal (z) directions with a resolution of 0.00254 cm (.001 in) and in the angular (θ) direction in the x-y plane with a resolution of 0.01 degree, were done through remotely controlled stepping motors. A 4 μ dia., 2.5 mm long tungsten hot-wire along with DISA equipment was used to obtain the instantaneous velocity signal. A Spectrascope SD335 spectrum analyzer (500 frequency lines) was used to obtain the velocity spectrum. The amplitudes (in dB) and frequencies (Hz) of the spectral peaks were read directly from the spectrum analyzer. The exit boundary layer thickness data were obtained/analyzed on-line with our laboratory minicomputer (HP 2100).

RESULTS AND DISCUSSION

The exit boundary layer momentum thickness $\theta = \int U/U_c (1 - U/U_c) dy$ was used as the characteristic length scale of the free shear layer and was determined at 3 mm upstream from the exit plane. Before the start of the excitation studies, the $\theta = \theta(Ue)$ functions were determined from boundary layer traverses in the two nozzles for the entire ranges of available speed; these functions were found to be repeatable within 2%; excitation amplitudes used for vortex pairing studies produced no noticeable changes in these functions. Subsequently, for each nozzle the θ value at any Ue was found directly from the corresponding $\theta(Ue)$ plot. Even though the exit boundary layer was not fluctuation free, the fluctuation intensity profiles in the nozzle exit boundary layer could be attributed to oscillations of laminar boundary layer [15]. The exit velocity profile shape factor was essentially that of the Blasius profile, i.e., 2.59. The exit boundary layer was thus assumed laminar for the entire range of speed used.

Investigation of the jet flow field revealed that pairing can occur with excitations at Strouhal numbers larger than $St_D = 0.85$. This, however, does not invalidate the findings reported in ref. [5]. It turns out that in order to detect these high Strouhal number pairing phenomenon, the probe has to be moved away from the centerline in the potential core towards the shear layer. As we will see, these pairings occur in the shear layer in the 'shear layer mode' as opposed to the 'jet mode' which involves the entire cross section.

Immediately downstream from the exit, the jet centerline is too far from the vortex core in the shear layer; the probe has to be close to the shear layer to capture the signatures of the passing rolled-up shear layer vortices or the associated coalescence event. We will present evidence which will suggest that a circular jet has two independent modes of instability and associated pairing: the shear layer mode and the jet mode.

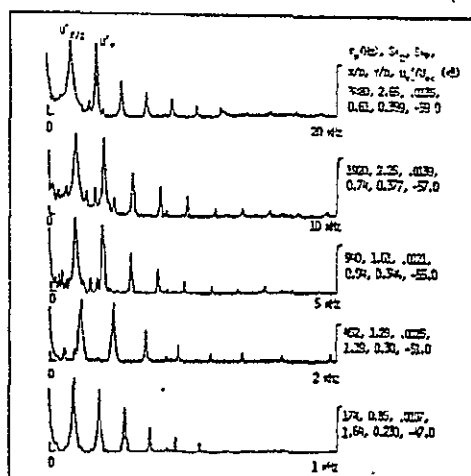


Fig. 1 Frequency spectra of the longitudinal velocity signal for shear layer mode excitations; jet dia: 2.54 cm. Vertical scales (log) are arbitrary and horizontal scales (linear) are indicated. The second peak in each plot represents the fundamental (f_p). Related information is indicated for each case.

Fig. 1 shows the one-dimensional frequency spectra of the longitudinal velocity u at the indicated off-centerline probe locations for the cases when vortex pairing can be inferred from the subharmonic amplitude. Note that for each location, the second peak in the spectra (from left) corresponds to the frequency of excitation while the subharmonic component can be attributed to the occurrence of pairing. (Even though the subharmonic component in a shear layer has been unambiguously related to vortex pairing, we intend to reaffirm this through flow visualization.) Note that for the five cases in Fig. 1 representing occurrence of vortex pairing (in the shear layer mode), the jet Strouhal number St_D ranges from 0.85 at $U_e = 5.21$ m/sec to 2.65 at $U_e = 33.2$ m/sec. However, the Strouhal number St_θ based on the shear layer exit momentum thickness θ is about 0.011 for all the cases. Similar data with the 7.62 cm dia. jet revealed occurrence of vortex pairing in the shear layer at a jet Strouhal number as high as $St_D = 8.0$ while the shear layer Strouhal number St_θ remained about 0.011. This is the 'shear layer mode' and is the same phenomenon studied by Freymuth [7], Winant and Browand [8], Brown and Roshko [2] and many others.

On the other hand, as first shown in ref [5], stable vortex pairing occurs in the jet at the jet Strouhal number $St_D = 0.85$ over a large range of jet Reynolds number (ie. independent of St_θ). This is the 'jet mode' and we have confirmed its occurrence at $St_D = 0.85$ over a St_θ range of 0.001-0.015.

These are the two 'modes' for a circular jet in which controlled excitation induces strong vortex pairing in the near field. We have failed to observe any indication of vortex pairing with excitations at Strouhal numbers significantly different from both $St_D = 0.85$ and $St_\theta = 0.011$. In the following sections we present data to establish the occurrence of, as well as the characteristics of these two modes.

A series of experiments using hot-wire techniques were undertaken to find the nondimensional characteristic parameters controlling velocity fluctuation amplification and vortex pairing in circular jets. The experiments were carried out for each jet according to the following scheme. For a fixed excitation frequency f_p and probe location in the potential core, the amplitudes of the different harmonic contents in the longitudinal one-dimensional velocity spectrum were found out as a function of the exit speed. The relative exit excitation level u_e'/U_e was set at a preselected value, at a speed that resulted in the shear layer mode pairing; this level varied slightly with the exit speed and was higher at lower speeds and lower at higher speeds. The detailed considerations employed in choosing the excitation level and the probe locations will not be discussed here because they are not central to the results presented here. For a limited number of cases, similar amplitude variation data were obtained keeping the exit speed and relative excitation level the same but varying the excitation frequency. This latter scheme could not be used at all exit speeds because sinusoidal surging of adequate level could not be obtained at appropriate frequencies corresponding to each speed U_e .

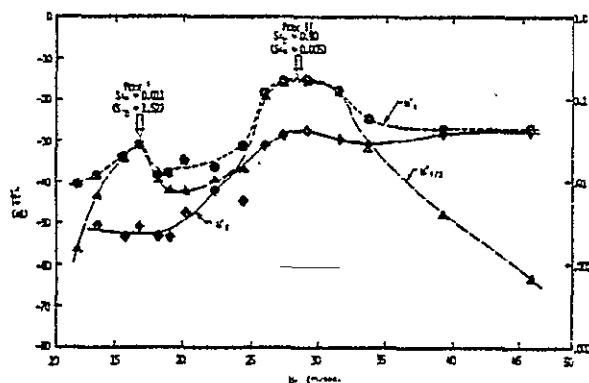


Fig. 2a Variations of the fundamental (u'_f) and subharmonic ($u'_f/2$) amplitudes and the total rms turbulence intensity (u'_{rms}) as a function of exit speed U_e for the 2.54 cm jet; $f_p = 1004$ Hz; $u_{ec}'/U_{ec} = 1\%$; $U_{ec} = 19.0$ m/sec; probe at $x/D = 2.0$ on the centerline.

Fig. 2a shows a typical plot of the fundamental and subharmonic amplitudes as a function of the exit speed U_e ; the total turbulence intensity variation is shown for comparison. Note that the subharmonic amplitude peaks at two exit speeds. The total rms intensity, being a result of all the harmonic contents, also shows peaks at these conditions indicating that at these two states the subharmonic component is extremely strong and the rms value of the entire signal is essentially due to the subharmonic. The fundamental component varies much more monotonically. As we will see, whenever pairing occurs, the measured peak turbulence intensity is mostly due to the motions associated with the vortex pairing. Thus very little can be inferred about the jet sensitivity from the fundamental amplitude variation.

The striking feature of these two peaks in all similar plots is that the one on the left (Mode I) corresponds to a value of St_θ in the range 0.010 - 0.014 while the Mode II corresponds to a St_θ value in the range 0.75 to 1.0. It is to be emphasized that, these two parameters could be varied over a wide range; viz., St_θ from 0.0001 to 0.20 and St_θ from 0.02 to about 50.0. However, spectral data indicated that vortex pairing could be induced in the jet only when either $St_\theta = 0.011$ or $St_\theta = 0.85$.

$St_\theta = 0.011$ has been found by different investigators [16,17] to correspond to the frequency at which a given shear layer is most unstable. Given a shear layer without any particular applied disturbance, the roll-up into vortices tend to occur at the most unstable mode of the shear layer and this natural roll-up occurs at a frequency that corresponds to $St_\theta = 0.011$. This together with the fact that a constant St_θ is associated with the first peak (Fig. 2a) indicates that the first mode is associated with the jet exit shear layer instability and hence the name 'shear layer mode'. The second mode of vortex pairing (Mode II in Fig. 2a), on the other hand, always occurs at $St_\theta = 0.85$, scaling on the jet diameter D and hence named the 'jet mode'.

The shear layer mode, when St_θ is high, is found to involve more than one stage of pairing; the peak of the subharmonic amplitude curve in such a case no longer corresponds to $St_\theta = 0.011$. However, the peak of the lowest subharmonic amplitude variation in such a case corresponds to $St_\theta = 0.011$. This is shown in Fig. 2b which is a similar plot as Fig. 2a but for the 7.62 cm jet at $f_p = 70$ Hz; the probe

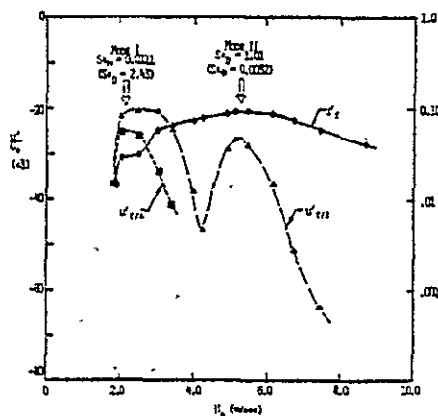


Fig. 2b Amplitude variations of u_f , $u_f/2$, $u_f/4$ and $u_f/8$ with exit speed U_e for the 7.62 cm jet; $f_p = 70$ Hz; $u_{ac}/U_{ec} = 3\%$, at $U_{ec} = 2.4$ m/sec; probe at $x/D = 0.67$ on the centerline.

position is such as to bear identical geometric location as that used for the data in Fig. 2a. Note that the $u_f/4$ spectral component has its peak at a velocity corresponding to $St_\theta = 0.011$. As we shall see later, the $u_f/4$ component extracts energy from the $u_f/2$ component as a result of which the peak of the subharmonic $u_f/2$ in such a case is flattened out and its mean no longer corresponds to $St_\theta = 0.011$. Note that the second peak in Fig. 2b corresponds to $St_\theta = 1.0$.

The optimum speeds for the formation of the two modes as found from the two peaks in Figs. 2a, b are not artifacts of the probe locations used. These peaks occur, of course with varying relative amplitudes, independent of the location of the probe. Fig. 2c

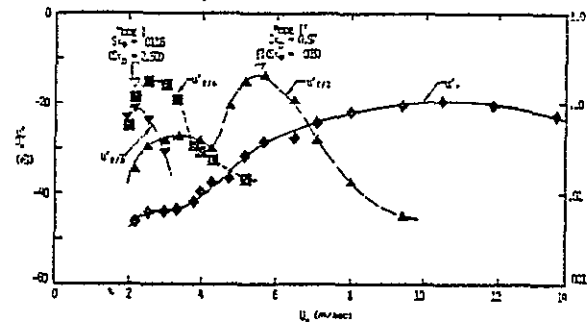


Fig. 2c Amplitude variation of u_f , $u_f/2$, $u_f/4$, $u_f/8$ and u_f with exit speed U_e for the 7.62 cm jet; $f_p = 70$ Hz; $u_{ac}/U_{ec} = 3\%$ at $U_{ec} = 2.4$ m/sec; probe at $x/D = 2.0$ on the centerline.

shows similar data obtained with the probe located on the centerline for the same flow condition as for Fig. 2b, but for probe location at $x/D = 2.0$ instead of at $x/D = 0.67$. The amplitudes of the different spectral components are plotted as a function of exit speed. In this case however, a third stage of pairing associated with the shear layer mode occurs for a small range of velocities and the peak of the $u_f/8$ component now corresponds to $St_\theta = 0.0116$, while the $u_f/4$ and $u_f/2$ components have broader peaks.

The jet mode does not show any successive subharmonic beyond the first indicating that either only one pairing occurs in the jet mode or that a second pairing occurs so far downstream that no significant motion is induced by the pairing process at $x/D = 2.0$. It is not going to be easy to resolve this question as the random turbulence becomes so dominant after the first jet mode pairing that any other stage of pairing, even if present, will be obscured.

Data (similar to those in Figs. 2a-c) with different relative excitation amplitudes but for fixed probe location show (not presented here) that the Strouhal numbers for the two modes are the same as indicated above i.e. $St_\theta = 0.011$ and $St_\theta = 0.85$. Note that the spectral components, including the fundamental, cannot be distinguished clearly from the background turbulence after 5 diameters downstream. Very near the exit, on the other hand, the subharmonic peaks become too weak to be distinguished from the background turbulence and electronic noise.

In order to further confirm the Strouhal numbers associated with the two modes of vortex pairing it is desirable to show the jet response for fixed velocities but varying frequencies of excitation. However, the frequencies of excitation, being determined by the cavity resonance frequencies of the settling chamber combination, cannot be varied continuously; also, amplitude of excitation achievable depends on the settling chamber resonance modes. However, for a limited number of cases at relatively lower frequencies (f_p) it was possible to obtain such data which also showed the existence of the two modes. Fig. 2d shows the (7.62 cm) jet response data as a function of

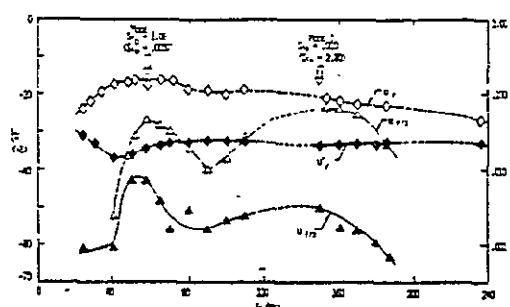


Fig. 2d Amplitude variations of u_f^2 and $u_f^2/2$ with excitation frequency f_p for the 7.62 cm jet at constant $U_e = 4.1$ m/sec for two probe locations: (i) $x/D = 0.20$ and centerline (solid data points) (ii) $x/D = 0.20$ and $U/U_c = 0.95$ point near the shear layer (open data points).

excitation frequency at a fixed speed $U_e = 4.1$ m/sec; the dashed portion indicates frequency range where necessary exit excitation level was unattainable. A second probe was placed at the jet exit and the relative excitation level was adjusted to the same value at each frequency. This figure covers two experiments with the probe at two transverse locations but at the same downstream distance from the exit - one at the centerline (open data points) and the other near the shear layer at $U/U_c = 0.95$ (solid data points). Amplitude variation for only the fundamental and subharmonic frequencies are recorded and no noticeable $u_f^2/4$ component could be discerned in the spectra. As is evident, the subharmonic curves are characterized by two distinct peaks - the one on the right now represents the shear layer mode and the other the jet mode.

From several plots similar to the ones in Figs. 2a-c, 12 for each of the two jets, the loci of the

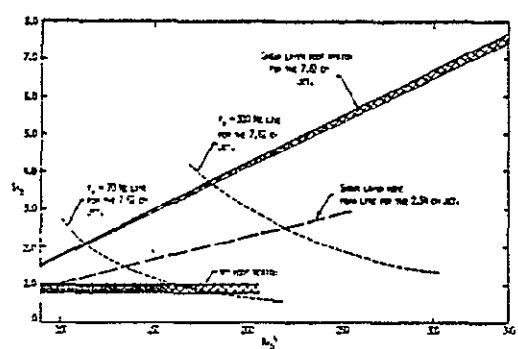


Fig. 3 Conditions for strong vortex pairing in the shear layer mode and the jet mode.

shear layer and the jet mode subharmonic peaks are shown on a St_D vs $Re_D^{1/2}$ plot in Fig. 3. For the jet mode, the region is terminated on the right because

the second peak (Figs. 2a-c) becomes progressively broader with increasing Re_D and location of the second peak becomes ambiguous in such cases. Both the regions terminate on the left (Fig. 3) due to difficulty in measurements at low velocities and/or non-availability of very low excitation frequencies. The shear layer mode plot is limited on the right by the maximum speed available and/or maximum available excitation frequency of sufficient amplitude. Note that on a St_D vs Re_D plot, while the shear layer mode curves for the two jets would coincide, the jet mode curves for the two jets would be apart.

Fig. 3 also includes two constant frequency (f_p) lines for the 7.62 cm jet. It is clear that for excitation at $f_p = 70$ Hz, as the Reynolds number is varied, the subharmonic amplitude will be large at $Re_D^{1/2} = 113$ and 170. However, at higher frequencies, for example at $f_p = 310$ Hz, the jet mode region cannot be reached with the maximum Re_D available; a plot similar to Fig. 2 for such f_p is characterized by only one peak corresponding to the shear layer mode at $St_D = 0.011$.

In order to further understand the shear layer mode, the downstream spectral evolution in the shear layer was studied with the probe placed near the layer, viz at a location where $U/U_c = 0.70$. Fig. 4 shows the downstream variation of the rms of the

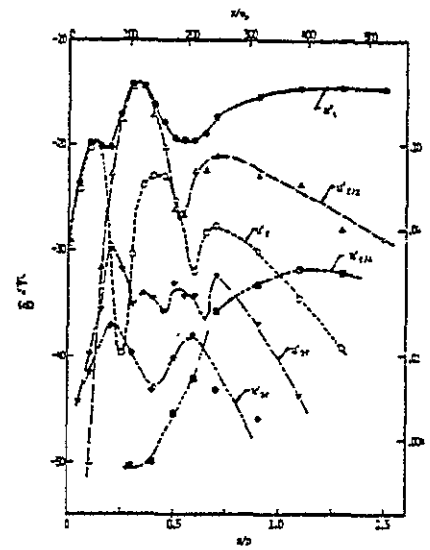


Fig. 4 Spectral evolution downstream along the $U/U_c = 0.70$ line for the 7.62 cm jet at $St_D = 0.011$ ($St_D = 3.77$); $f_p = 308$ Hz; $u_{ec}/U_{ec} = 1\%$; $U_e = 6.22$ m/sec.

total as well as of the spectral components for the 7.62 cm jet for excitation at $St_D = 0.011$. The exit velocity and f_p were chosen such that St_D was quite high (3.77) so that no appreciable effect from the jet mode interfered with the shear layer data.

While the higher harmonic amplitudes show considerable scatter in the data due to background noise, the $u_f^2/4$, $u_f^2/2$ and u_f^2 spectral components

exhibit well defined trends. The higher harmonics merely represent the existence of a non-sinusoidal signal with the period of the fundamental (or subharmonic) and thus has no bearing on the shear layer vortex scale size or spacing. The higher harmonics thus are of little significance in our discussion.

With increasing x , the fundamental amplitude increases, then saturates at $x/D = 0.13$ before starting to decay. The saturation and decay of the fundamental is associated with the growth of its harmonics, but more importantly with that of the subharmonic. The subharmonic extracts its energy from the fundamental and the maximum growth rate of the subharmonic roughly coincides with the maximum decay rate of the fundamental. The subharmonic grows to an amplitude larger than the fundamental due to addition of kinetic energy of two like signed vortices, saturates further downstream at $x/D = 0.30$ and then decays. The saturation of the subharmonic generates its own harmonics and thus contributes to u_f' which, as a result, exhibits a rise in its amplitude. The $u_f'/4$ component similarly grows at a maximum rate where the decay rate of $u_f'/2$ is maximum and saturates further downstream contributing energy to both u_f' and $u_f'/2$ components, both of which as a result exhibit rise in amplitude at that location. The spectral components give in to turbulence afterwards and no further pairing could be identified. Note that up to $x/D = 0.1$ the total velocity fluctuation is due to fundamental only. At $x/D = 0.3$ the fluctuation is essentially due to the subharmonic, which is stronger than the fundamental. However, the second subharmonic is not as strong because during the time elapsed to reach this stage transition sets in.

Figs. 2a-d clearly indicate that the maximum growth of the subharmonic for the shear layer mode occurs at $St_\theta = 0.011$. To confirm this, the streamwise evolution of the subharmonic amplitude (along the $U/U_c = 0.70$ line) is shown in Fig. 5 for a few St_θ cases. The peak amplitude at the subharmonic frequency occurs at $St_\theta = 0.011$; no subharmonic peaks could be discerned in the velocity spectra below $St_\theta = 0.004$ and above $St_\theta = 0.015$. Note also that $St_\theta = 0.011$ produces the most rapid growth of the subharmonic, its peak occurring nearest to the exit. The second peak at $St_\theta = 0.011$ also suggests that its second subharmonic is the strongest.

It is to be noted that the St_θ for which the fundamental amplitude grows the most is not 0.011. Independent studies of shear layer instability [16,17] clearly indicate that the natural roll-up of a shear layer occurs at $St_\theta = 0.011$. It thus appears that this natural instability and roll-up in an axisymmetric free shear layer is also the one most conducive to subharmonic formation.

The growth of the subharmonic for the jet mode as a function of x/D for different St_θ 's is plotted in Fig. 6; for all the cases shown here, the exit excitation level was kept constant at $u_{ec}/U_{ec} = 3\%$. This figure confirms that for the jet mode, the maximum growth of the subharmonic occurs at $St_\theta = 0.85$. The subharmonic formation did not occur for cases below $St_\theta = 0.6$ and above $St_\theta = 1.6$. As will be seen, the latter case is associated with strong suppression of the centerline total turbulence intensity as compared to the non-excited case.

The fundamental amplitude variation along the jet centerline as a function of x/D for different St_θ 's is documented in Fig. 7. Maximum growth of the fundamental occurs at $St_\theta = 0.30$ which has also been

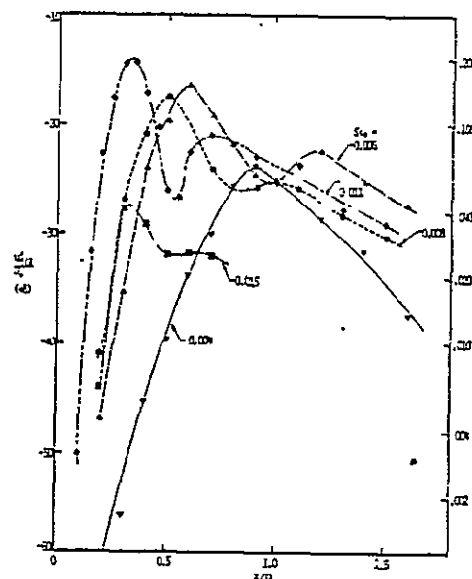


Fig. 5 Downstream variation of the subharmonic amplitude ($u_f'/2$) along the $U/U_c = 0.70$ line at different St_θ (i.e. different U_e) for the 7.62 cm jet. $f_p = 308$ Hz; $u_{ec}/U_{ec} = 1\%$ (constant).
 ∇ $St_\theta = 0.004$ ($St_D = 1.53$); $\triangle$ 0.006 (2.48);
 $\circ$ 0.008 (3.02); $\diamond$ 0.011 (3.77); $\square$ 0.015 (4.69).

found by Crow and Champagne [11] to be the jet 'preferred mode'. Crow and Champagne [11] also found the generation of a subharmonic at $St_D = 0.60$. They argued that $St_D = 0.60$, being double the preferred mode, was most susceptible to produce the (strongest) subharmonic in order for the disturbance to get back to the preferred mode. The pairing phenomenon being nonlinear, such an argument, applicable to a linear system, appears unjustified. Current data show that the growth of the subharmonic reaches its maximum at $St_D = 0.85$ which is not the first (or any) harmonic of $St_D = 0.30$. The fundamental amplitude for the cases associated with vortex pairing e.g. $St_D = 0.85$, 1.0 etc exhibit oscillations similar to the shear layer mode as explained in connection with Fig. 4. However, the near-exit drop in the fundamental amplitude (see ref. [5]) at $x/D = 0.12$ remains unexplained. Note that the fundamental at $St_D = 1.6$ shows monotonic decrease with increasing x .

The downstream variation of the total longitudinal turbulence intensity on the centerline for the 7.62 cm jet are shown for different St_θ 's in Fig. 8. The total amplitude roughly follows the amplitude of the largest spectral component at any point but becomes higher than any one of them further downstream where onset of turbulence occurs. Note that although $St_D = 0.30$ shows large amplitude (u_f') growth and is considered to be the preferred mode, the growth of the subharmonic at $St_D = 0.85$ results in comparable or even higher amplitude for the total fluctuation intensity. $St_D = 1.6$ shows a suppression of the centerline turbulence intensity, even below the

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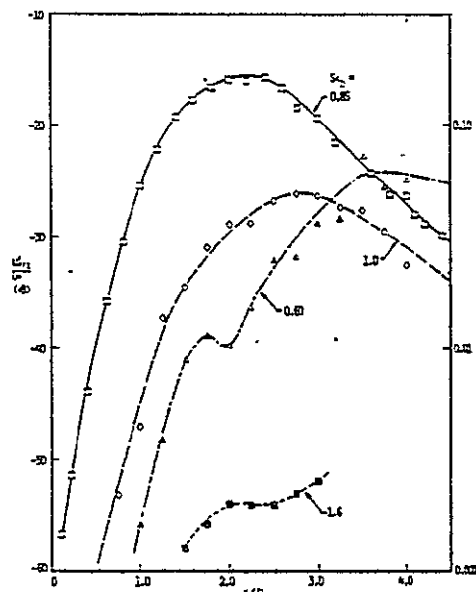


Fig. 6 Subharmonic amplitude variation with x/D along the jet centerline at different St_D 's for the 7.62 cm jet. $u_{ec}/U_{ec} = 3\%$ (constant); $\square$ $St_D = 0.85$ ($St_\theta = 0.0025$), $Re_D = 32,000$; $\diamond$ $St_D = 1.0$ ($St_\theta = .0026$), $Re_D = 43,000$; $\blacksquare$ $St_D = 1.6$ ($St_\theta = 0.0041$), $Re_D = 43,000$; $\triangle$ $St_D = 0.60$ ($St_\theta = 0.0016$), $Re_D = 41,600$.

non-excited case. The suppression effect reported previously [5] is still unexplained. Recent data indicate that this suppression effect is dependent on Re_D . Vlasov and Ginevskiy [14] reported suppression at $St_D = 2.75$ but provided no explanation. This point constitutes a topic of our continuing research in this field.

The streamwise spectral evolution for the jet mode (7.62 cm jet) at $St_D = 0.85$ is shown in Fig. 9. Note that immediately downstream from the exit, the signal is due to the fundamental component which saturates due to the growth of the subharmonic through pairing. Pairing produces an intensification of the induced velocity and the subharmonic grows and reaches a maximum at $x/D = 2\frac{1}{2}$ before saturation. In this region the total signal is essentially due to the subharmonic. Saturation of the subharmonic contributes partially to u_f component which as a result shows a rise again. The discussion here essentially follows that in connection with Fig. 4.

Fig. 10 documents only the subharmonic evolution at $St_D = 0.85$ along the jet centerline for three different cases: (i) for the 7.62 cm jet with laminar exit boundary layer when $St_\theta = .0025$, (ii) same condition as in (i) except that the exit boundary layer was tripped to make it turbulent [see ref. 5 for details], (iii) for the 2.54 cm jet at $St_D = 0.85$ but $St_\theta = 0.0106$. The subharmonic evolution for these three cases are essentially identical. Note that case (ii) eliminates shear layer structure and thus the effect of the shear layer mode on the

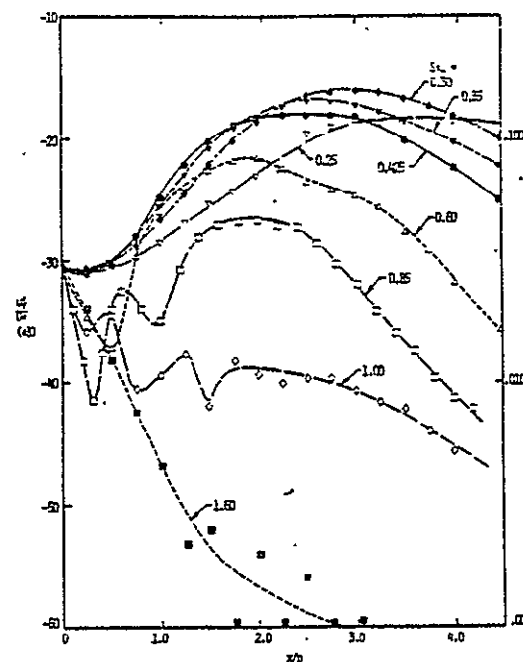


Fig. 7 Fundamental amplitude variation along the centerline of the 7.62 cm jet at different St_D . $u_{ec}/U_{ec} = 3\%$ (constant). The different parametric values for each case in the order, St_D (St_θ), f_p , Re_D , are as follows: ∇ 0.25(.0006), 32 Hz, 50,000; $\diamond$ 0.30(.00078), 32 Hz, 41,600; ∇ 0.35(.00091), 37 Hz, 41,600; $\bullet$ 0.425(.0011), 45 Hz, 41,600; $\triangle$ 0.60(.0016), 64 Hz, 41,600; $\square$ 0.85(.0025), 70 Hz, 32,000; $\diamond$ 1.0(.0026), 110 Hz, 43,000; $\blacksquare$ 1.6(.0041), 174 Hz, 42,800.

jet mode. On the otherhand, case (iii) was chosen such that both the shear layer mode and the jet mode would occur simultaneously.

Figure 10 thus suggests that the jet mode is independent of the shear layer characteristics, and that the jet mode is independent of the shear layer mode. The jet mode is neither a legacy of the shear layer mode as commonly assumed nor does the shear layer mode affect the jet mode in any significant manner. It thus seems that the vortex pairing occurring at $St_D = 0.85$ is not initiated or governed by the initial shear layer instability.

Concluding Remarks

Vortex pairing in circular jets can occur in two distinct modes: the shear layer mode and the jet mode. The shear layer mode is associated with the exit shear layer instability mechanism and the strongest pairing occurs when the excitation frequency matches the natural roll-up frequency. Strouhal number based on exit boundary layer momentum thickness θ for this mode of vortex pairing is found to be $St_\theta = 0.011$. In the jet mode of vortex pairing, the phenomenon scales on the jet diameter and most pronounced pairing occurs at $St_D = 0.85$. The velocity fluctuation intensity in the near field of

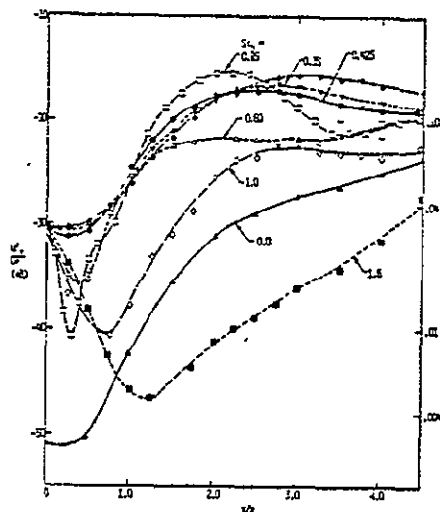


Fig. 8 Variation of the total longitudinal turbulence intensity along the centerline of the 7.62 cm jet at different St_D . $u_{ec}/U_{ec} = 3\%$; other parametric values associated with each St_D are the same as indicated in Fig. 7. $Re_D = 41,600$ for the unpulsated case ($St_D = 0.0$).

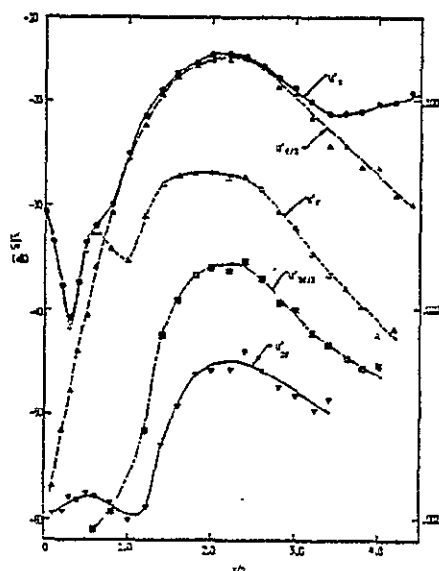


Fig. 9 Amplitude variation along the centerline of the different harmonic components in the u -signal of the 7.62 cm jet at $St_D = 0.85$ ($St_\theta = 0.0025$); $f_p = 70$ Hz; $Re_D = 32,000$; $u_{ec}/U_{ec} = 3\%$.

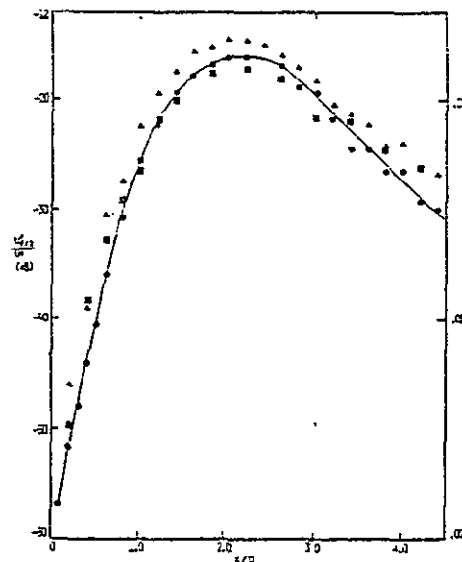


Fig. 10 The variation of the subharmonic ($u_2/2$) amplitude along the jet centerline at $St_D = 0.85$ for three cases: (i) $St_D = 0.85$, $St_\theta = .0025$, $Re_D = 32,000$, $f_p = 70$ Hz for the 7.62 cm jet; (ii) same conditions as in (i) except that exit boundary layer is made turbulent by tripping; (iii) $St_D = 0.85$, $St_\theta = .0107$, $Re_D = 8,900$, $f_p = 174$ Hz for the 2.54 cm jet.

a round jet reach relative maxima when it undergoes vortex pairing in either of the two modes.

When excited at the shear layer mode, and when the corresponding St_D is relatively high, the vortex rings rolled up shortly downstream from the exit is found to undergo more than one stage of pairing. It is plausible, in line of Laufer and Browand's [1], argument that the independence from the initial length scale (θ) and dependence on the jet diameter (D) as length scale further downstream may be achieved through successive stages of vortex pairing. However, as our data indicate, the jet mode of excitation can also initiate and govern the downstream coherent structures in a round jet. Although the instability mechanism involved in the jet mode is not yet well-understood, orderly structures scaling on the diameter of the jet seem to form in the near field without being influenced by the shear layer instability.

ACKNOWLEDGEMENT

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The Free Shear Layer Edgetone and Instability Measurements

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Summary

The shear tone phenomenon has been explored with a hot-wire in axisymmetric and plane free shear layers and is found to be different in many ways from the slit jet-wedge edgetone.

Introduction

Hot-wire measurements of the natural instability frequency of a free shear layer, in connection with our study of the organized structure in a circular jet [1] revealed that the probe itself can trigger and sustain upstream instability modes like the slit jet-wedge edgetone. This phenomenon is appropriately termed the free shear layer tone.

All known jet edgetone experiments have been carried out in slit-jets originating from laminar channel flow. Theory in this field is still inadequate, but most notable ones [2,3] rely on counter-rotating line vortices originating from the two lips of the slit-jet to trigger the jet pendulation. The free shear layer, being inherently different from the initially fully vortical slit jet, was expected to produce a different tone behavior; hence the motivation for this study.

The experiments were carried out in the incompressible free shear layers of a plane and a circular air jet facilities, described respectively in [1] and [4]. For all the measurements reported here, the initial boundary layers producing the free shear layers were documented (at 0.2 cm upstream from the lip) and were classified as laminar [4].

Results

Fig. 1 shows the schematic of the flow and the coordinate system. Fig. 2 shows the peak frequency f of the hot-wire signal as a function of the hot-wire distance x from the lip of the plane free shear layer along $U/U_e = 0.5$. Roman numerals indicate stage of the tone. In the overlap (bimodal) region there are two spectral

peaks. Unlike in the jet-wedge edgetone, the shear tone in the bimodal zone occurs only in one mode (i.e. stage) at a time while intermittently switching between the two modes. The dotted line in Fig. 2 indicates the value of x beyond which the higher stage has a larger amplitude than that at lower x ; the overlap region is shown only for $U_e = 37.2$ m/s. Data on the lower right hand side represent the subharmonic frequencies, attributed to vortex pairing. The subharmonic peak is quite broad, decreasing in amplitude with increasing x until it is submerged in the evolving background turbulence. It is remarkable that organization of the flow due to shear tone feedback from the probe stem tip brings out the subharmonic associated with vortex pairing, which otherwise would occur randomly in space and time and would not be discernible in the velocity spectrum of a free shear layer without any tone. Fig. 3 shows similar data in the axisymmetric free shear layer; overlap and subharmonic frequencies also occur but have not been shown. The rest of this paper pertains to plane mixing layers only.

Fig. 4 shows variation of the tone frequency f with U_e at a fixed hot-wire location $x = 1.02$ cm, $U/U_e = 0.95$. The circles represent data taken while increasing U_e and the triangles while decreasing U_e . The data failed to show any evidence of hysteresis i.e., the jump frequency is independent of whether, U_e is being increased or decreased, or x is being increased or decreased. This aspect of the shear tone is different from the jet edgetone where hysteresis occurs for variations in x or in U_e . Fig. 5 shows the streamwise variations of the shear layer tone frequency nondimensionalized by the local momentum thickness θ . These data suggest that the non-parallel aspect of the free shear layer alone would not provide an explanation for the shear tone.

Figs. 2 and 3 show that for any given geometry and U_e , the measured shear layer instability frequency can vary widely depending on the probe location. Even when the probe is used in the configuration shown in Fig. 1, it is possible to determine the true instability frequency by traversing the probe in x , and noting the x (thus the frequency) which gives the largest spectral peak. This peak fre-

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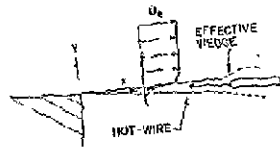


Fig. 1

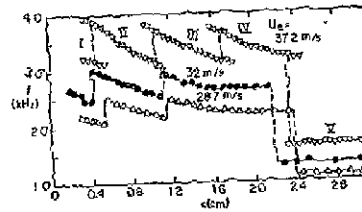


Fig. 2

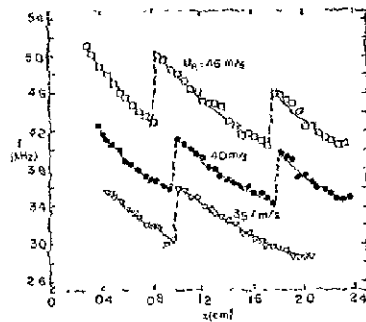


Fig. 3

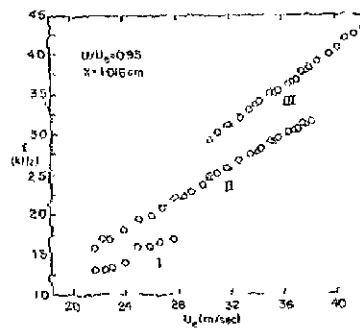


Fig. 4

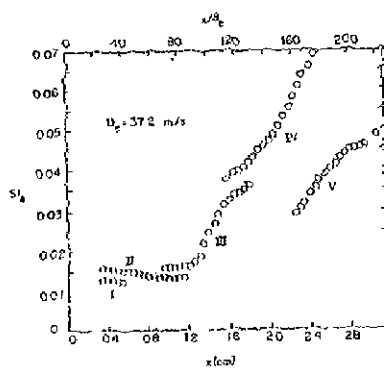


Fig. 5

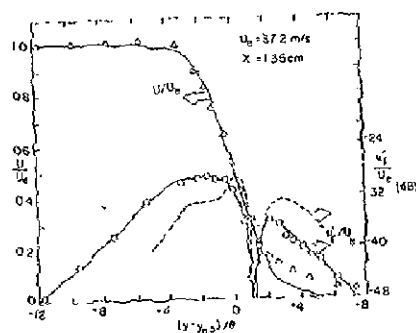


Fig. 6

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quency is the true instability frequency and occurs at about the middle of each stage.

The longitudinal mean velocity distribution for $U_e = 37.2$ m/s at $x = 1.35$ is compared with the tanh-profile (solid line) in Fig. 6. Most of the large disagreement on the zero-speed side is attributable to effects of large fluctuations and transverse entrainment velocity on the hot-wire, and the exit boundary effects. Profile of the rms amplitude of the fundamental is also shown in Fig. 6 and compared with the spatial theory of Michalke [5]. While the data and theory do not agree well, as to be expected [6], the agreement on the location of zero amplitude is impressive.

Further study was carried out with a 20-degree wedge aligned with the flow and located at $U/U_e = 0.5$. The hot-wire was then used to explore the flow field while making sure that the stem, inclined at about 60 degrees to the flow, did not intersect the flow.

Fig. 7 shows the nondimensional frequency fh/U_e as a function of h/H , where H is the plane jet width. The shear layer tone differ from the jet-wedge edgetone where $fh/U_e(h)$ has been found to be constant in each stage [7]. However, fh/U_e vs h/θ_e plot shows collapse of all the data in each stage (Fig. 8), confirming that

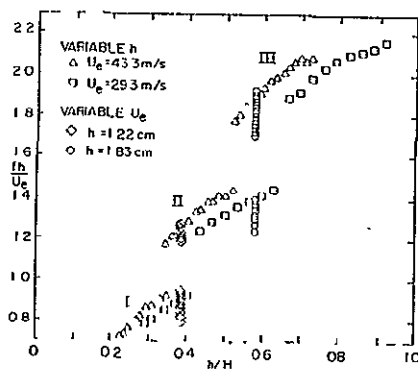


Fig. 7

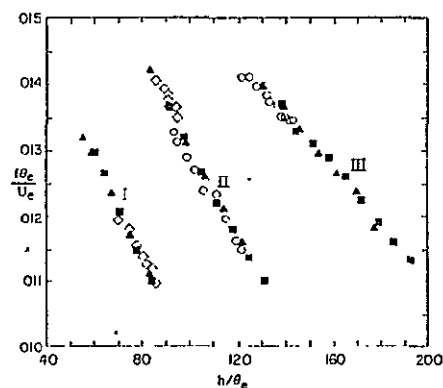


Fig. 8

the phenomenon is influenced by the initial condition. The free shear layer tone eigenfunctions, i.e., the amplitude and phase profiles, as well as eigenvalues, i.e., the frequency-dependent phase velocity and wavenumber have been determined for a range of h and U_e . The data suggest that the feedback is hydrodynamic rather than acoustic. Of special interest is the dependence of the wavelength on the lip-wedge gap h . Many jet-wedge edgetone investigators have confirmed the Brown-Curle relation $h \approx (J + 1/4)\lambda$, where J is the stage of edgetone. The corresponding relation for the first two stages of the free shear layer tone is found to be $h \approx (J + 1/2)\lambda$. Further details of the shear layer tone is being investigated by hot-wire and flow visualization.

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