NOISE MEASUREMENTS OF A LOW REYNOLDS NUMBER SUPERSONIC JET

By

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

a_o	ambient speed of sound
C	convection velocity of instability waves in flow
d	effective jet diameter
D	nozzle exit diameter
f	frequency
M_j	Mach number of jet
p_{ch}	chamber pressure
p_n	nozzle exit pressure
p_o	stagnation pressure of jet
r	spatial coordinate (See Figure 1)
Re	Reynolds number based on nozzle exit diameter
St	Strouhal number
T_o	stagnation temperature of jet
U	centerline mean jet velocity
x	downstream spatial coordinate (See Figure 1)
y	vertical spatial coordinate (See Figure 1)
z	longitudinal spatial coordinate (See Figure 1)
ζ	azimuthal angle (See Figure 1)
θ	noise radiation angle relative to jet axis (See Figure 1)
μ	Mach angle
λ_a	acoustic wavelength perpendicular to wavefronts
λ_i	flow instability wavelength

λ_o wavelength of periodic cell structure in jet

λ_r acoustic wavelength in radial direction

λ_x acoustic wavelength in axial direction

CHAPTER I

INTRODUCTION

When a supersonic jet exhausts from a nozzle an intense acoustic radiation field is generated. This radiation field is a significant contributor to the noise pollution problem. Its effects can be heard in industrial plants, where compressed air jets exhaust to atmosphere, as well as airports where jet aircraft produce considerable noise problems.

Lighthill's classical formulation (1, 2), concerning the aerodynamic generation of sound, set the ground work for the theoretical investigation of the jet noise problem. Although, Lighthill's formulation was originally devised specifically for subsonic jets, his basic approach has been extended to the supersonic regime by numerous other investigators (3, 4). Application of these theories, however, requires accurate experimental measurements of flow disturbances. However, measurements of this type have proved to be extremely difficult to obtain and have never been satisfactorily accomplished.

Recently, a number of theoreticians have formulated the supersonic jet flow development in terms of linear stability theory with Tam's work being the most extensive (5, 6, 7). Tam's model includes the effects of the periodic cell pattern of expansion and shock waves by which a supersonic jet adjusts to the ambient pressure after exiting from a nozzle. Even in the case of the nearly ideally expanded jet (which is the case Tam considers) these waves, though of infinitesimal strength, many exert a controlling influence on the development of the jet disturbance.

In Tam's model the jet is assumed to be inviscid with an infinitesimally thin shear layer. A constant jet velocity parallel to the jet axis is assumed. When the results of linear stability theory are mathematically combined with the constraints imposed by the periodic cell pattern, selective amplification of two disturbance frequencies is predicted. Tam considers the higher of the two frequencies unimportant in its contribution to the generated noise field. The lower frequency is, however, considered a dominant contributor to the noise levels measured in the radiation field of the supersonic jet. An important feature of Tam's approach is that only mean flow conditions are needed to calculate his results. These conditions can be easily determined experimentally.

Tam has proceeded to advance his work by predicting a number of the acoustic radiation properties of the nearly ideally expanded supersonic jet. Comparisons of Tam's results with acoustic measurements on supersonic jets exhausting to atmosphere have shown general agreement. However, since Tam's analysis is based on linearized disturbance equations, direct comparisons of his results can be accomplished only with a supersonic jet which has an initially laminar flow. At sufficiently low Reynolds numbers the turbulence intensity levels in the jet are low enough to justify dropping the non-linear terms from the disturbance equations.

The basic thrust of the supersonic jet noise research program at Oklahoma State University has been to provide the experimental measurements necessary to evaluate directly the linear stability approach to jet noise prediction. In accordance with this motivation microphone measurements have been made in the acoustic radiation field along with hot-wire anemometer measurements in the flow field of low Reynolds number supersonic jets. This thesis will deal mainly with the acoustic studies, however, comparisons with hot-wire measurements performed on the same jets under similar flow conditions will be presented whenever appropriate. For further details on the hot-wire measurements mentioned see Morrison (8).

The four major objectives of this thesis are: (1) Comparisons between flow measurements and acoustic measurements will be made to determine whether the amplified instability waves in the low Reynolds number supersonic jet are the dominant noise producers, (2) Acoustic radiation field measurements made in the low Reynolds number jets will be compared with published measurements of high Reynolds number jets exhausting to atmosphere in order to establish whether similarities exist between the two conditions, (3) The orientation of the acoustic wave fronts propagating from the jet will be determined so that comparisons of these results with the established properties of Mach wave propagation can be made, and (4) An examination of the effects produced on the acoustic radiation by varying the periodic cell structure of the jet through changes in the expansion condition will be performed.

To establish more clearly the relationship between the objectives of this thesis and the physical situation under study a schematic is presented in Figure 1 showing some of the general features of the supersonic jet and its acoustic radiation. This figures is based on Tam's view of the supersonic jet flow development. In this model of the nearly ideally expanded supersonic jet random small scale disturbances are present in the flow at the nozzle exit. As these disturbances are convected downstream selective amplification of specific disturbance frequences occurs. This selection process is governed by the periodic cell structure of the jet. These disturbances grow as an exponential function of downstream position for several jet diameters until a large scale coherent undulation of the entire jet results. After this initial period of growth broadening of the mixing layer between the jet and the ambient air causes dampening and eventually disintegration of this coherent disturbance. Tam believes the oscillations of this large scale disturbance are responsible for a dominant portion of the jet's acoustic radiation.

Since stability theory predicts large scale disturbance waves moving at a velocity greater than the ambient speed of sound, Mach wave type radiation of the generated noise would be suggested. Indeed, shadowgraphic observations made by Lowson and Ollerhead (9) of the acoustic wave fronts propagating from a region around 10 diameters downstream of the jet exit exhibit a pattern of strong Mach wave type radiation. However, the stability analyses to date have not directly predicted this property, and it is still a matter of some debate.

Tam suggests that the frequency of this large scale disturbance comes at the peak of the broad range of frequencies present in the spectral analysis of the noise from a fully turbulent supersonic jet. The broadening of the spectral peak present in measurements by investigators such as Dosahjh and Yu (10) is attributed to the turbulent mixing of the jet caused by the dominant oscillation.

In the low Reynolds number jet the levels of the noise generated by the turbulent mixing will be insignificant compared to the total noise level. Because of this feature the effects of the dominant instability on the noise radiation should be perfectly clear.

CHAPTER II

EXPERIMENTAL CONSIDERATIONS

This study has been performed in the free jet test section of the Oklahoma State University supersonic wind tunnel. A schematic is shown in Figure 2. Three axisymmetric supersonic de Laval nozzles were used in the research. Their exit diameters, D, were 6.35 mm, 9.52 mm, and 15.2 mm. All three nozzles were used to demonstrate that the effects studied were due to the jet and not the chamber geometry. The two small nozzles (6.35 mm and 9.52 mm) were converging-diverging axisymmetric nozzles with simple conical exit sections with half angles of 1.60 degrees and 2.28 degrees respectively. The 15.9 mm nozzle has contoured walls designed by the method of characteristics to provide uniform flow at the nozzle exit.

The jet facility is operated by evacuating its downstream section. The Reynolds number of the flow can then be varied by adjusting the stagnation pressure, p_o, upstream of the nozzle. All measurements done in this study were in a Reynolds number range from 8060 to 14,600. This contrasts with a Reynolds number of $1.3x10^6$ one obtains for a 10mm jet at a similar Mach number exhausting to atmosphere.

The jet exhausts into a rectangular chamge of inside dimensions 33 cm by 39 cm by 23 cm. The inlet to the jet is a 15 cm diameter stilling section. To reduce the turbulence levels upstream of the nozzle a 5 cm section of foam rubber and six fine screens are located in this stilling section. Room air was used for the jet's supply with a stagnation temperature, T_o, of 530^{o}R. The balance condition between the nozzle exit pressure and the chamber pressure is adjusted by a variable throat diffuser, located inside the chamber downstream of the nozzle exit.

A 1/8 in. diameter Bruel and Kjaer condenser microphone type 4138 was used for the acoustic measurements. The microphone was mounted on a two-dimensional probe drive in a plane vertically intersecting the jet axis (x and y dimensions). The microphone has an omni-directional response within $\pm$ 3 db for frequencies up to 60 kiloHertz. The chamber was lined with 1/2 inc. acoustical tile to dampen the standing and reflected sound waves. A frequency analysis of the signal was then accomplished using a Hewlett-Packard model 302 wave analyzer and a Mosely model 2d x-y plotter. The Hewlett-Package analyzer has a bandwidth of 6 hz. A General Radio Model 1910 A wave analyzer with a bandwidth of 100 Hz. was used to determine whether any major spectral effects were deleted by the narrow band analyzer.

In the Reynolds number range of these experiments viscous effects can have an effect on the jet Mach numbers. To evaluate the actual Mach numbers of the jets pitot and static pressure measurements were made on the centerline of the two smaller nozzles (see Morrison (8)). The average Mach numbers between the jet exit and two diameters downstream were M=2.2 for the 6.35 mm jet and M=2.3 for the 9.52 mm jet. The Mach number in this region of the 15.9 mm jet was estimated from hot-wire measurements to be 2.5. Average Mach numbers were presented because of the wave cell effects on the local Mach numbers even at a p_n/p_{ch} ratio between 1.01 and 1.00 (where p_n/p_{ch} indicates nozzle exit pressure divided by chamber pressure).

There are two methods to establish the orientation of the acoustic wave fronts propagating from the amplified disturbances in the jet. In the first approach two microphone probes are located in the radiation field simultaneously. With one probe acting as a reference the other probe is moved relative to it. Correlation of the two microphone signals enables one to determine the relative phase differences between the two signals. In this manner the phase distribution of the acoustic signals in the radiation field may be determined. This method has two disadvantages. One disadvantage is the interference caused by the physical presence of the reference probe in the acoustic field. The other disadvantage is the problem of making an acoustic correlation between two complicated electronic signals, one from each probe.

The second approach is the one followed in this study. In this method an artificial exciter is used as the reference signal. The exciter inputs a disturbance frequency at the nozzle exit. This disturbance is kept at a power level which is insignificant compared to the total jet energy. If the exciter frequency is adjusted to a frequency which is selectively amplified by the jet, relative phase measurements in the radiation field are possible. This second approach overcomes both major disadvantages of the first. Since the exciter signal is a single frequency, correlation of the two signals is much easier; and since the reference probe is eliminated, probe interference effects are removed.

Artificial excitation of the jet was produced by a glow discharge exciter similar to one used by Kendall (11) in a boundary layer stability study. The tip of a .04 inch diameter tungston wire was used as the electron emitter of the discharge. The tungston tip was located inside the nozzle about two mm. from the exit. The tungston wire was biased to a 450 volt negative potential by a DC power supply drawing less than 2 ma. An 800 volt peak to peak oscillation of the exciter was produced by a Hewlett-Packard model 206a Audio signal generator, a McIntosh MC 75 power amplifier and a Triad HSM-186 output transformer. The power level of the exciter was calculated to be less than two percent of the total jet energy flux.

CHAPTER III

EXPERIMENTAL RESULTS

To show that the jet is initially laminar in the Reynolds number range of these experiments hot-wire fluctuation measurements were made in the flow immediately downstream of the nozzle exit by McLaughlin and McColgan (12). These measurements demonstrate that at a Reynolds number of 14,700 the jet is initially laminar with peak fluctuations less than 5% of the local mean mass flux. The fluctuations grow and spread through the jet until the jet appears fully turbulent at nine nozzle diameters dowmstream. These results indicate that the jet characteristics are compatible with the governing, linearized equations in Tam's model.

To prove that the acoustic effects measured were characteristic of the jet and not due to the geometry of the flow facility, spectra on three different nozzles are presented in Figure 3. These spectra are presented in terms of the non-dimensional frequency St=fd/U where f is the frequency, d is the effective jet diameter (the exit diameter of the nozzle, D, minus twice the boundary layer displacement thickness at the nozzle exit) and U is the mean jet velocity. The balance condition, p_n/p_{ch} was between 1.05 and 1.01 for all spectra. Examination of the spectra shows that a dominant acoustic signal comes at a similar value of non-dimensional frequency, St, in each of the three diameter jets. This result indicates that the dominant components of the acoustic radiation are characteristic of the jet and not the chamber geometry. The strong low frequency acoustic signals (below St=.02) present in the spectra are due to resonance effects caused by the finite size of the exhaust chamber. One does not expect these effects to be present in the acoustic spectra of jets exhausting into open space.

Notice that the largest peak of each spectrum is located near St=0.18. This frequency compares with the peak of the acoustic spectra measured by Yu and Dosanjh (13) of St=0.15 in a fully turbulent supersonic jet at M=1.5. It also compares closely to Tam's predicted amplified disturbance frequency of St=0.19. Another important observation which can be made from the spectra is that a tendency for more than one dominant spectral component is present. This effect seems to be in contradiction with Tam's prediction of a single amplified disturbance frequency. This contradiction will be discussed in more detail later in this thesis.

Figure 4a shows a representative hot-wire spectra taken in the flow 5 nozzle diameters, 5D, downstream of the nozzle exit. Figure 4b shows a representative microphone spectra taken at a position 3.5D below the jet axis and 9D downstream from the 6.35 mm nozzle exit under approximately the same flow conditions as the hot-wire spectra. Both spectra exhibit many of the same dominant peaks; although, some of the spectral components have different relative magnitudes. Spectra like these, verify that the dominant fluctuations within the flow are indeed prominent noise generators. Morrison (8) has shown that these dominant mass flux fluctuations have properties consistent with the instability waves of linear stability theory.

It may be possible that different frequency instability modes in the jet may have different noise production efficiencies. To further confuse this process the relative magnitude of the prominent peaks in the hot-wire and microphone spectra were observed to change from day to day even though flow conditions were monitored closely.

Other jet noise researchers have observed this phenomena. Chan and Westley have noticed changes in relative mode amplitudes due to the introduction of reflective surfaces near jet flows. The microphone and hot-wire probes constitute potential reflective surfaces. Also changes in the acoustic power from jets due to different air humidity conditions have been noted by Hiller, et al. (14). The room air, which is the supply for the jet, changes humidity with atmospheric conditions. Both of these effects could be influencing these measurements somewhat. However, the important conclusion that dominant instabilities in the flow are major noise producers seems justified.

Figure 5 shows sound pressure level contours of the 6.35 mm jet with a Mach number of 2.2. Frequencies below 3 kHz were filtered from the microphone signal in order to eliminate resonant effects in flow facility. These contours indicate general radiation field characteristics similar to pressure contours measured in jets exhausting to atmosphere (13, 15, 16). Sound pressure levels of a high Reynolds number supersonic jet measured by Mayes, et al. (17) are presented in Figure 6. The individual sound pressure levels are lower than the levels measured at atmospheric pressure. However, when a scaling factor of 24 db (determined from the ratio of atmospheric pressure to the chamber pressure) is added to the present measurements, levels approaching those measured at similar non-dimensional locations in the high Reynolds number jets are realized. These values are given in parenthesis on the figure. Based on these comparisons an important conclusion can be reached. This conclusion is that the apparent noise producing mechanism of the high and low Reynolds number jets appear to be basically equivalent.

To determine the orientation of the acoustic wave fronts propagating from the jet, relative phase measurements were used. To accomplish these measurements the 6.35 mm jet was artificially excited by a glow discharge located near the nozzle exit. The effect of the excitation on the acoustic spectra is shown in Figure 7. Figure 7a shows a spectra with no artificial excitation. Figure 7b and 7c show the effect on the spectra of excitation at two different frequencies, St.=0.14 and St=0.18 respectively. It should be noted here that the exciter had no effect on the acoustic spectra unless the frequency of the excitation was tuned to a naturally occurring mode of the spectra. For this reason the excitation should be considered primarily as a triggering device serving as a reference for obtaining the acoustic phase measurements. The most significant effect on the spectra was observed when the jet was excited at St=0.18. Because of this effect and since the Strouhal number was near Tam's predicted mode, all acoustic relative phase measurements were performed at this exciter frequency with the jet balance pressure p_n/p_{ch} between 1.005 and 1.01.

The relative phase measurements were obtained by determining the phase difference between the microphone and exciter traces using a dual-beam oscilloscope. Figure 8 shows a typical oscilloscope trace in a 1/5 second time history photograph. To obtain phase locking of the signals the exciter signal was brought to a minimum voltage level where the frequency of the microphone trace was observed to lock to the exciter trace. Phase changes in the two signals could then be determined by moving the microphone along the x or r axis.

Figure 9 presents the results of relative phase measurements obtained by moving the probe in the downstream (x) direction at a radial location r/D=4. The slope of the plot and its 95% confidence interval determined from a least squares linear regression is $\lambda_x/D=3.35 \pm .09$. Similarly, figure 10 gives a typical phase plot in which the microphone was transversed in the radial (r) direction at an axial location of x/D=11. The slope of this plot and its 95% confidence interval is $\lambda_r/D=5.35 \pm .45$. Microphone phase measurements were repeated on a number of different days. The overall results are presented in Table I. These measurements displayed a small degree of deterministic error from day to day in addition to the random error determined from the least squares regression. This deterministic error was on the order of 10% of the measured values. The exact cause of this error was not identified although slightly different humidity or pressure balance conditions are suspected. No Reynolds number dependence was found for any of the wavelength measurements over the Reynolds range of this study.

Hot-wire measurements in the jet flow on the same nozzle at the same flow conditions indicate a disturbance wavelength of $\lambda_i/D=3.2 \pm .3$ (see Morrison (8)). The results of the hot-wire measurements are also shown in Table I.

At this point an important comparison should be recognized. The overall results of the disturbance wavelength measurement and the acoustic wavelength in the x direction are equal within the confidence intervals of the measurements. This comparison adds more evidence to

TABLE I

SUMMARY OF WAVELENGTH MEASUREMENTS

	Best Estimate	Total Uncertainty	Number of Experiments on Different Days	Total number of individual Phase Measurements
6.35 mm jet St=0.18				
λ_x/D	3.25	± 0.3 (10%)	7	86
λ_r/D	5.10	± 0.6 (12%)	3	32
λ_i/D	3.2	± 0.3 (10%)	3	30

indicate that the dominant acoustic waves in the radiation field are being generated by the large scale instability of the flow.

By using the acoustic wavelengths in the x and r directions, the wavelength perpendicular to the acoustic wave fronts in the zero azimuth plane, and the angle which the wave fronts make with the x axis can be determined (see Figure 11). These are $\lambda_a/D=2.8 \pm .25$ and $\theta=57.5^o \pm 4^o$ respectively. A calculation of the wavespeed from the frequency and the wavelength gives a value of 332 m/sec. This wave velocity agrees with the ambient speed of sound in the chamber, a_o=342 m/sec, within the uncertainty of these measurements.

Another confirmation of the reliability of these results is to calculate the Mach angle associated with the convection velocity of the instability waves in the jet (C=392 m/sec) as determined by Morrison (8). This calculation yields $\mu=\sin^{-1} a_o/C = 60.2^o \pm 2^o$ which is within the experimental accuracy of the measured acoustic wave angle. These measurements indicate that the noise radiated from the dominant jet instability propagates as Mach waves. This finding is in agreement with shadowgraphic observation made by Lowson and Ollerhead (9) of a perfectly expanded jet with a Mach number of 2.47 exhausting to atmospheric pressure. Shadowgraphs made under the direction of W. Mayes at Langley Research Center, also show what appear to be Mach waves corresponding to a disturbance convection velocity of between 70%-80% of the jet velocity for a jet of Mach number 2.15 exhausting to atmosphere.

All of the measurements reported earlier in this study were obtained with the jet operating in a nearly ideally expanded condition i.e. $1.05 < p_n/p_{ch} < 1.02$. Figure 12 shows the effect of changing the balance condition on the acoustic spectra. Figure 12a displays a spectrum at a nearly ideally expanded condition i.e., $p_n/p_{ch} = 1.02$. In this spectra there is a group of naturally excited modes centered around St=0.16. This group of strongly amplified frequencies covers a Strouhal range of about 0.35. It was at first believed that at this expansion condition the periodic wave cell structure might not be of sufficient strength to satisfy Tam's model thus explaining the discrepancy between the present multimodal spectrum and his prediction of a single amplified frequency. This belief, however, cannot be supported by Figure 12b. The balance condition of $p_n/p_{ch} = 1.45$ in this figure should result in a periodic cell structure of more than sufficient strength to satisfy Tam's nearly ideally expanded jet model. Figure 12b instead of demonstrating amplification of a single frequency also shows numerous amplified modes grouped around St=0.13. From these measurements it appears Tam's present theory is incomplete with respect to the jet frequency mode selection process.

However, a comparison of Figure 12a and 12b does seem to establish an important effect. The center of the group of amplified modes shifts from St=0.16 to St=0.13 when the balance condition is changed from $p_n/p_{ch} = 1.02$ to $p_n/p_{ch} = 1.45$. Since all flow parameters except the balance condition, were identical the shift in Strouhal number can be only attributed to the change in wave cell structure due to the different expansion conditions. (A slight change in Strouhal number would also be noticed due to a change in the parameter, U/d, with the change in pressure balance condition. However, this effect can be neglected since it is on the order of only 5%.) According to Prandtl (17) the wave cell structure ofthe jet will have a wavelength in the x direction given approximately by $\lambda_o = 2\ d(M_j^2 - 1)^{\frac{1}{2}} / 2\beta_1$, where β_1 is a constant equal to 2.4, d is the diameter of the jet, and M_j is the jet Mach number. In an underexpanded condition the jet will expand to an effectively larger diameter and also to a greater Mach number. This expansion will result in a cell structure with a longer individual cell length. Centerline measurements of mean hot-wire voltage performed on the 6.35 mm nozzle for expansion conditions of $p_n/p_{ch} = 1.01$ and $p_n/p_{ch} = 1.5$ presented by Morrison (8) do show a substantial increase in cell length between the two expansion ratios. The cell length in the perfectly balanced condition is increased by approximately 20% when the jet is underexpanded to $p_n/p_{ch} = 1.5$. This increase is close to the percent shift in Strouhal number of the amplified mode group shown in the spectra of Figure 12. This result then seems to indicate that the cell length, λ_o, does play an important role in determining the region of amplified frequency modes.

This finding supports Tam's basic assumption regarding the governing role played by the periodic cell structure even in the nearly ideally expanded jet. Though Tam's theory is inadequate in predicting the multimodal phenomena presented it does predict an amplified mode quite close to those measured. On the basis of this measurement, although Tam's representation should not be considered complete, its basic approach does appear to hold substantial promise.

CHAPTER IV

SUMMARY AND CONCLUSIONS

The major results of this study support the use of an instability model for supersonic jet noise prediction. This model exhibits a frequency selection mechanism which is controlled by the periodic cell structure of the nearly ideally expanded supersonic jet. In this study the jet was operated in a low Reynolds number range with an initial region of laminar flow transitioning to fully turbulent flow at a location several diameters downstream of the nozzle exit. The low Reynolds number range was selected so that the effects produced by the amplified instability modes on the acoustic radiation field would be clearly apparent.

Four major objectives were outlined in the introduction of this thesis. The first objective was to determine whether the amplified instability waves in the low Reynolds number supersonic jet were dominant contributors to the acoustic radiation produced by the jet. A comparison of a representative microphone frequency spectra in the noise field with a hot-wire spectra in the flow under similar flow conditions presented considerable agreement. Many of the dominant modes present in the hot-wire spectra were also observed in the acoustic spectra. Further support for the dominant role exhibited by the amplified instability modes in the production of jet noise was illustrated in the artificial excitation process. Excitation of an unstable mode near the jet exit caused an amplification of the noise signal at a frequency exactly corresponding to the frequency of the exciter signal. This evidence leaves little doubt concerning the dominant contribution that the amplified instability modes make to the noise field.

A comparison of acoustic radiation field measurements made in the low Reynolds number jet with published measurements for the high Reynolds number case was the second objective of this study. Constant sound pressure amplitude contours were used to demonstrate the similarity of the present field characteristics with noise field measurements made by numerous other investigators of fully turbulent jets exhausting to atmospheric pressure. An important result of this measurement demonstrated that the noise levels at comparative nondimensional field locations in the low Reynolds number jet (when scaled to atmospheric pressure) were approaching the noise levels published by investigators of fully turbulent jets. These results indicate that the noise production mechanism in the two conditions may be similar.

The orientation of the sound waves propagating from the jet was investigated for an artificially excited jet. These measurements indicated that the sound propagation from the instability waves within the jet was consistent with a Mach wave concept. This observation was in agreement with shadowgraphic evidence showing strong Mach wave propagation from a fully turbulent supersonic jet in a region around 10 jet diameters downstream of the nozzle exit. This region coincides with an area of strong noise propagation shown in the sound pressure contours of the present study.

The final objective of this study was to examine the effects produced on the acoustic radiation by varying the periodic cell structure of the jet. This structure was modified by changing the jet expansion condition given by the pressure ratio p_n/p_{ch}. A lowering of the frequency of a band of amplified modes was observed when the ratio p_n/p_{ch} was changed from 1.02 to 1.45. This change in frequency was of the same order as the change in the jet cell length determined from hot-wire measurements. This result implied a definite relationship between the jet cell length and the frequency of the amplified acoustic waves. This frequency selection mechanism, controlled by the periodic cell structure of the jet is an important feature of the instability jet model formulated by Tam.

In conclusion, the results of the measurements made in this study present a strong case for the continued development of the instability approach to supersonic jet noise analysis.

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APPENDIX

FIGURES

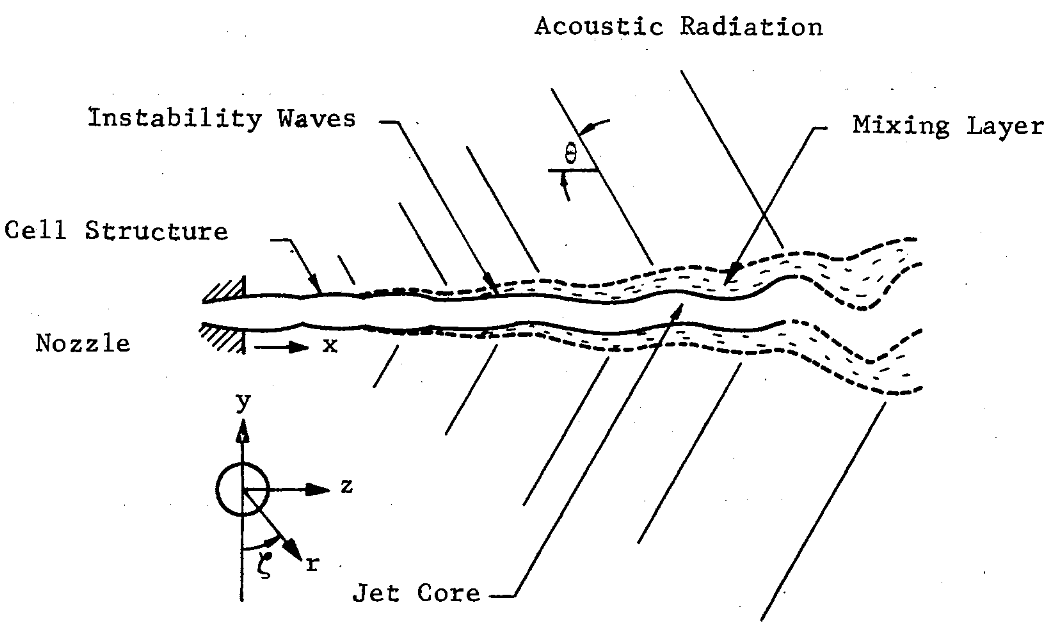


Figure 1. General features of the supersonic jet and its acoustic radiation

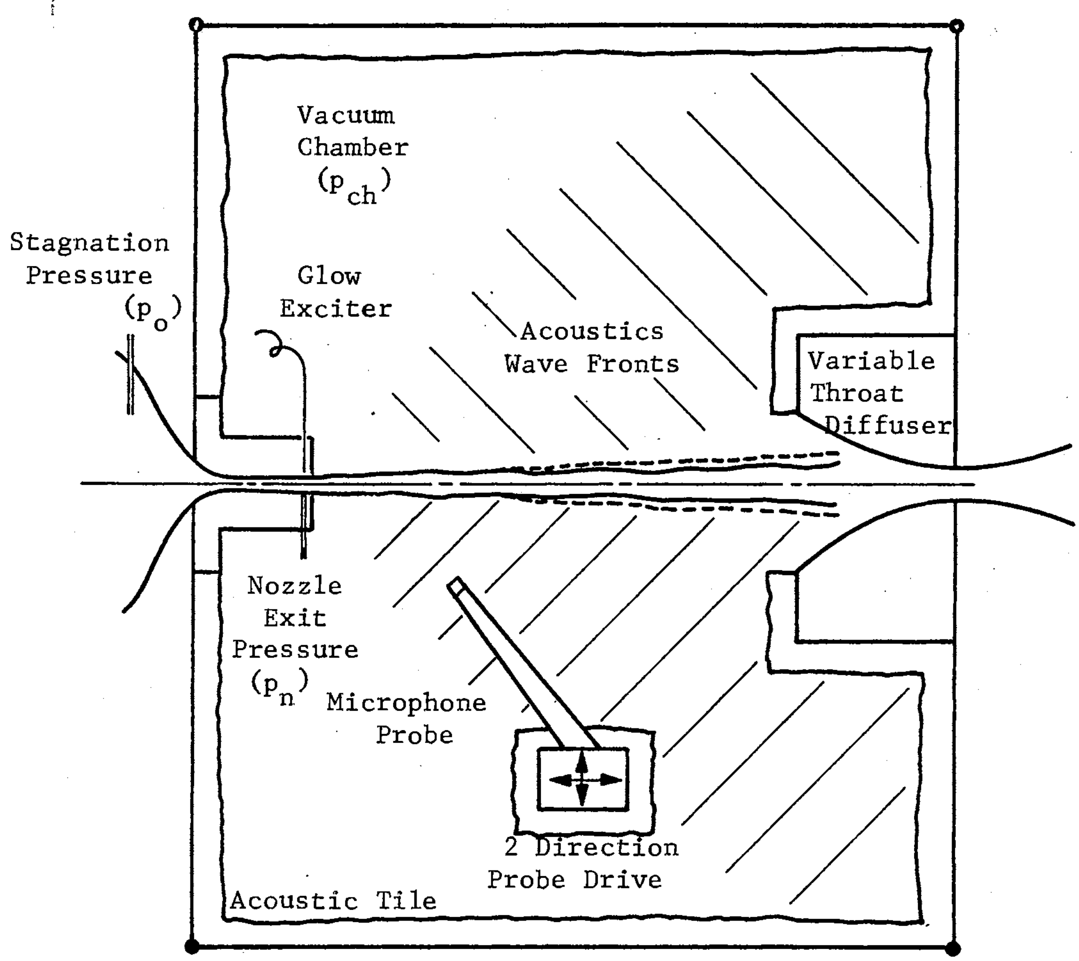


Figure 2. Schematic of the supersonic jet test facility

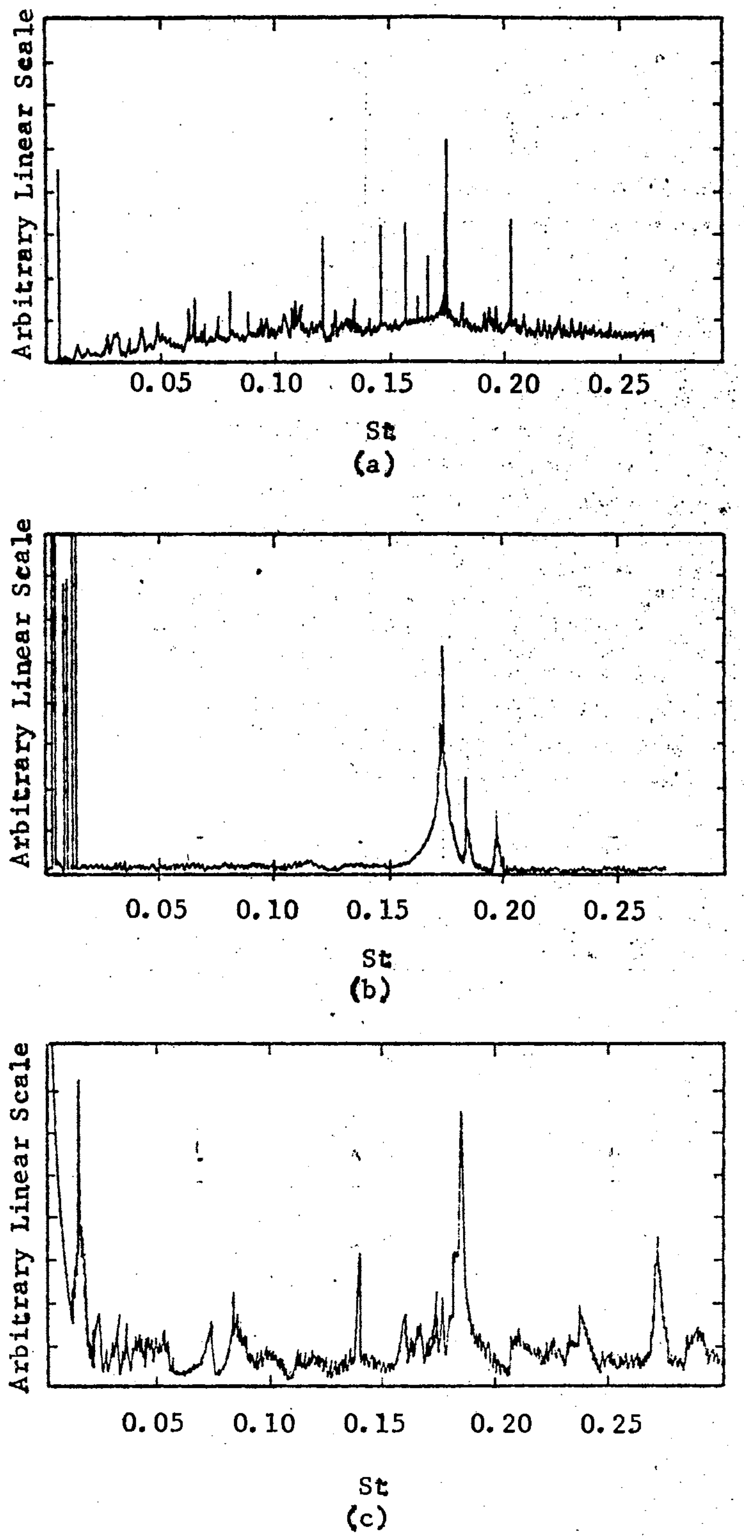


Figure 3. Microphone spectra in the radiation field of the supersonic jet. The band pass is 6 Hz and the sweep rate is 1000 Hz/min. (a) D=6.35 mm, Re= 14,400, U/d=108,000 sec^{-1}, (b) D=9.52 mm, Re= 11,000, U/d=67,800 sec^{-1}, and (c) D=15.9mm, Re=8060, U/d=39,600 sec^{-1}.

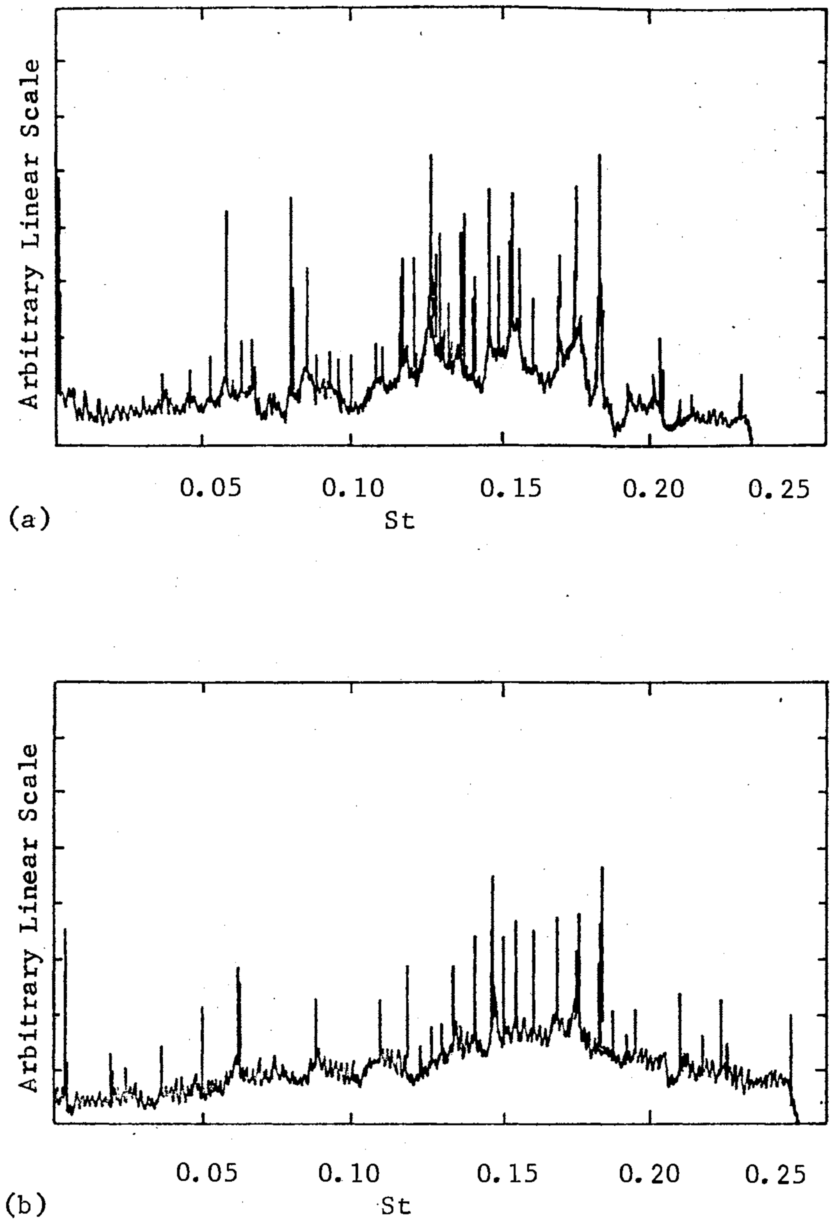


Figure 4. (a) Hot-wire frequency spectra with D=6.35 mm, p_n/p_{ch}=1.035, Re=14,900, x/D=5, (b) microphone frequency spectra with D=6.35 mm, p_n/p_{ch}=1.02, Re=14,350, x/D=9, r/D=3.5.

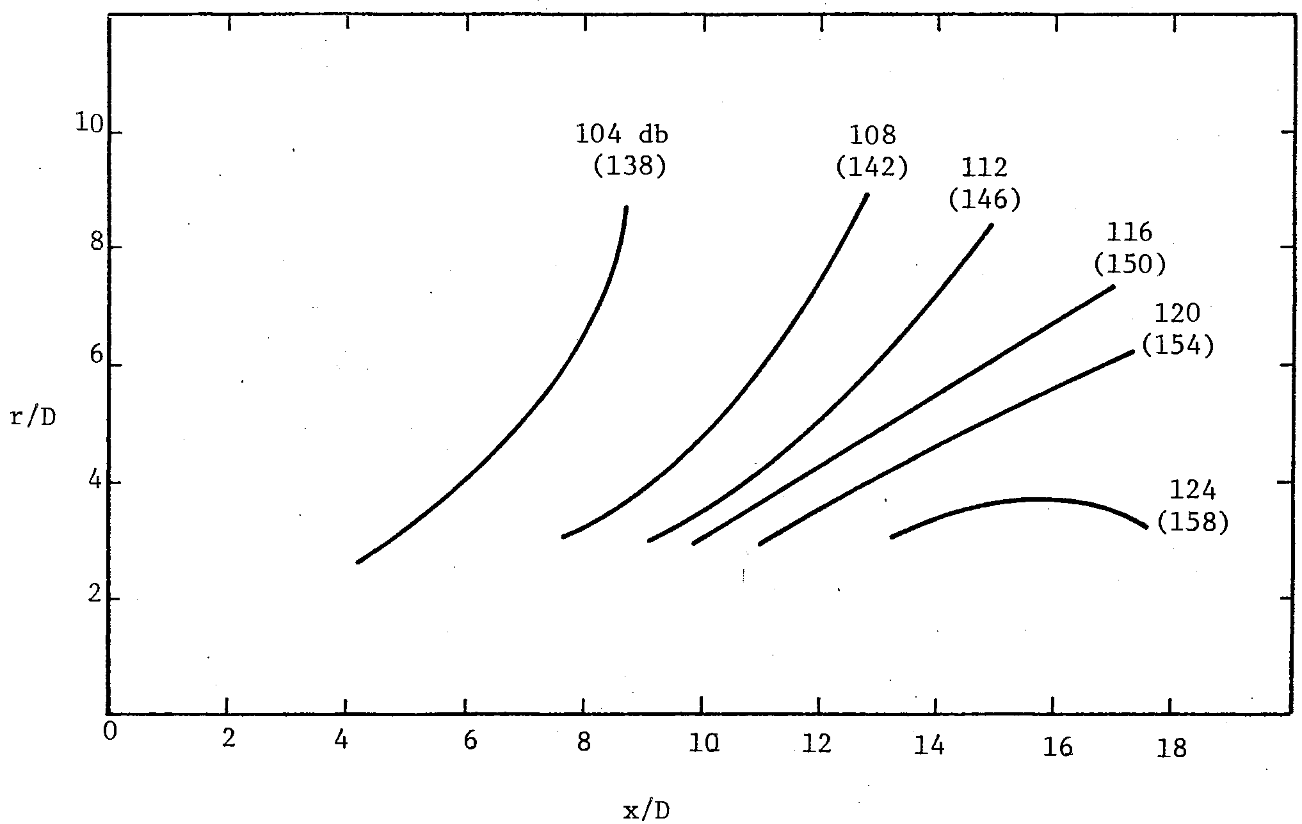
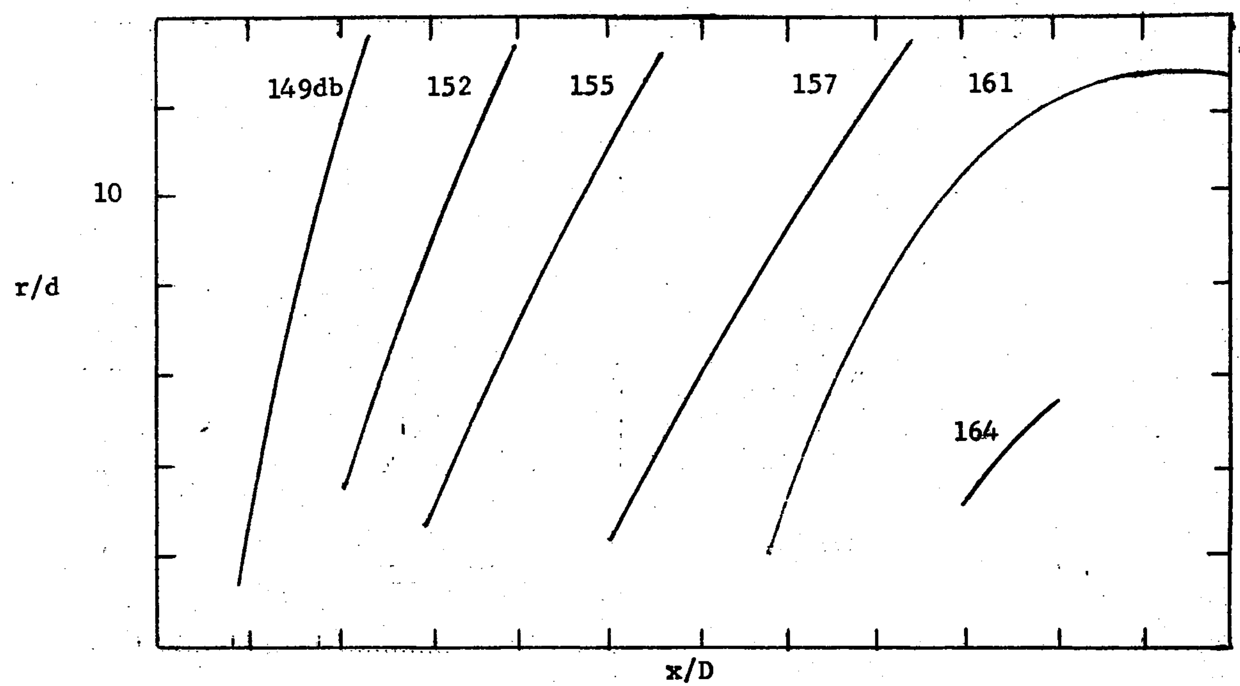


Figure 5. Microphone constant amplitude noise contours. Amplitudes scaled to atmospheric exhaust pressure in parentheses. Re = 12,600, D = 6.35 mm, p_n/p_{ch} = 1.01.



Source: W. H. Mayes, W. D. Lanford, and H. H. Hubbard. "Near Field and Far Field Noise Surveys of Solid Fuel Rocket Engines for a Range of Nozzle Exit Pressures." NASA TN D-21

Figure 6. Sound Pressure contours for high Reynolds number jet, M=2.6.

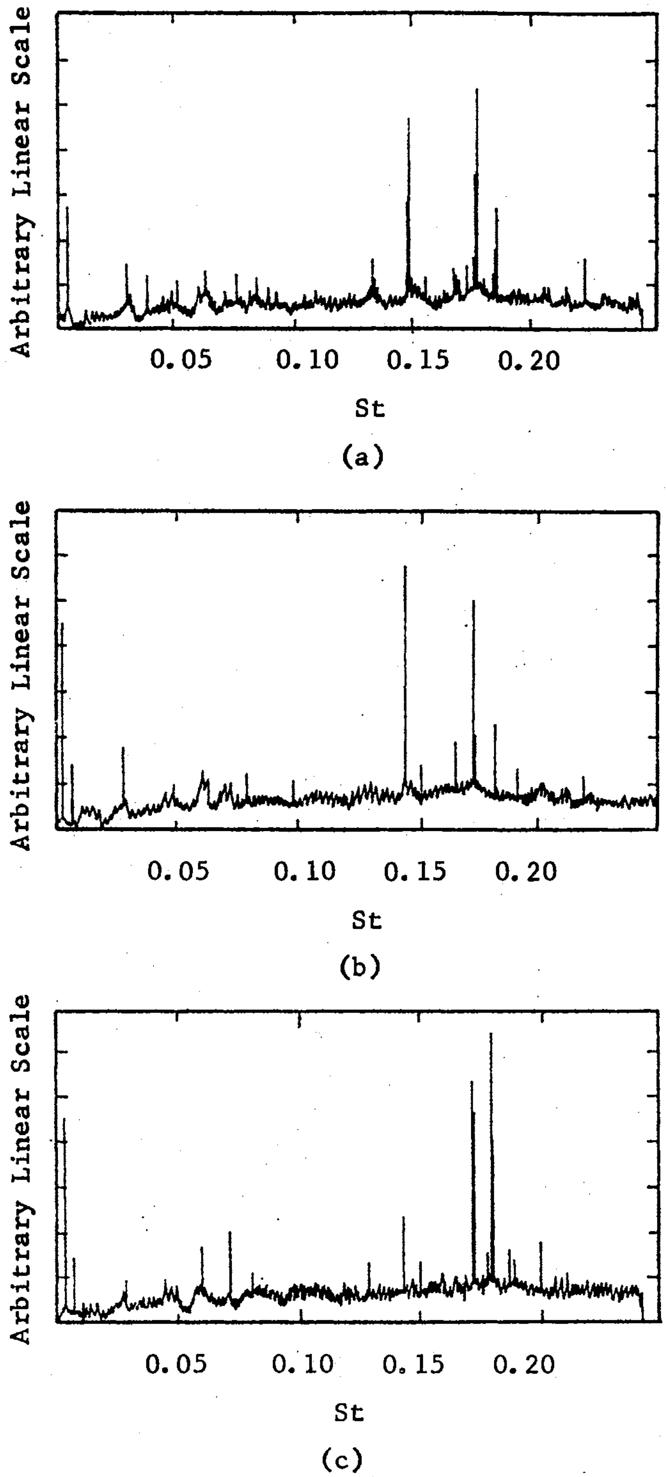


Figure 7. Effect of excitation on the microphone spectrum of the 6.35 mm jet at Re=14,400. (a) Naturally excited, (b) $St_{exciter} = 0.14$, (c) $St_{exciter} = 0.18$.

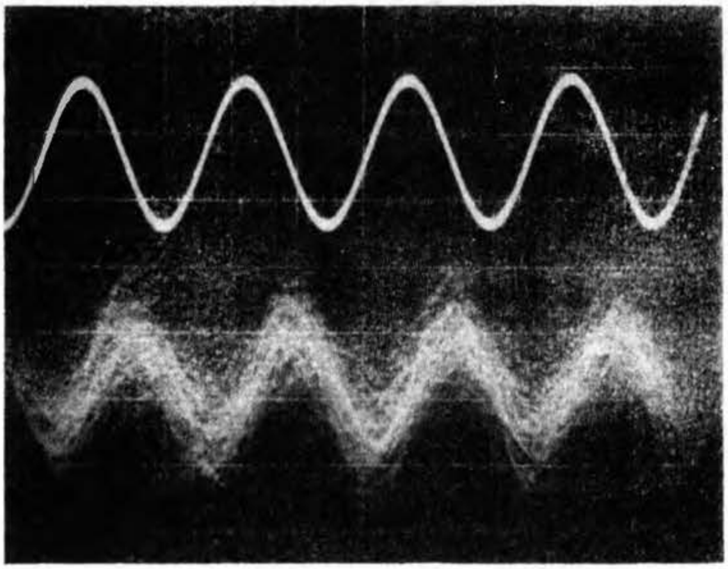


Figure 8. Oscilloscope trace of exciter signal (upper trace) and instantaneous microphone signal (lower trace) showing a typical phase locked situation. Re=14,000, $St_{exciter}$ = 0.18, and sweep rate=20μsec/cm.

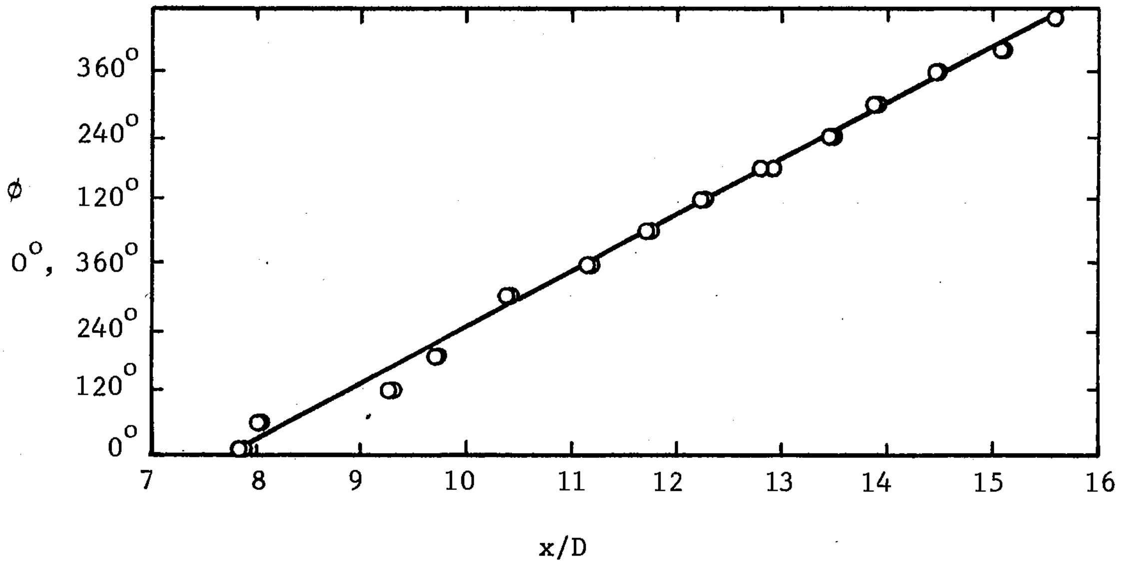


Figure 9. Axial distribution of microphone relative phase (ϕ). D = 6.35 mm, Re = 11,600, and St = 0.18.

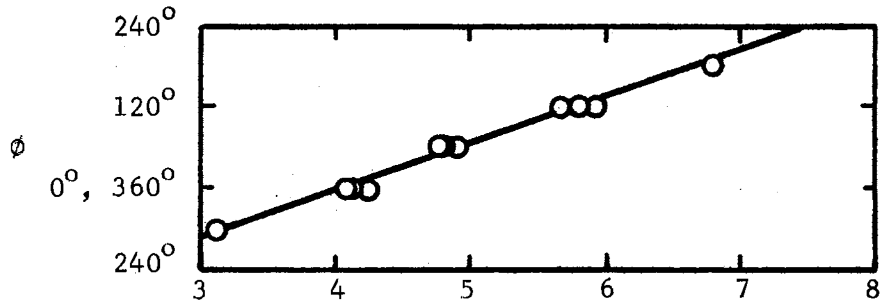


Figure 10. Radial distribution of microphone relative phase (ϕ). D = 6.35 mm, Re = 11.600 and St = 0.18.

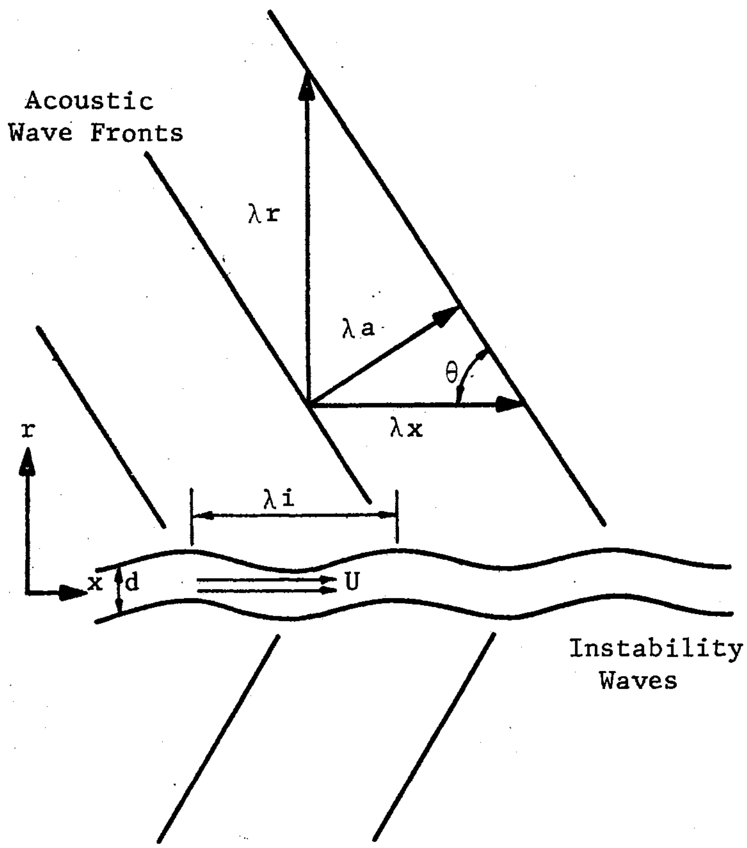
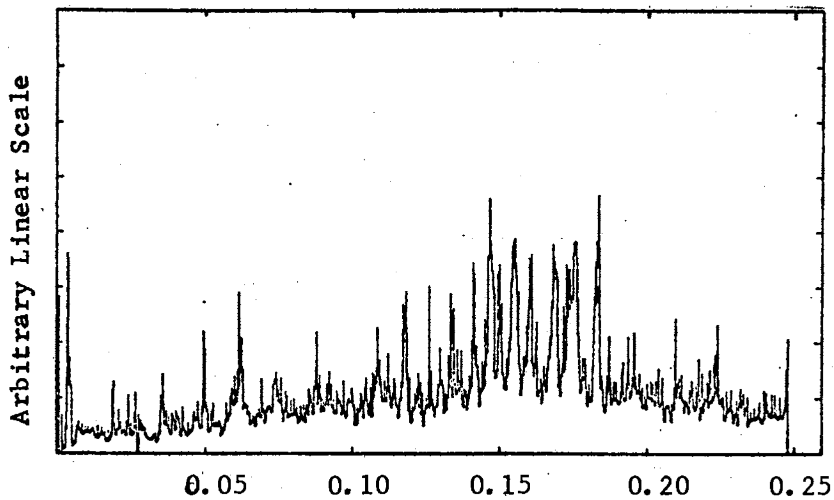
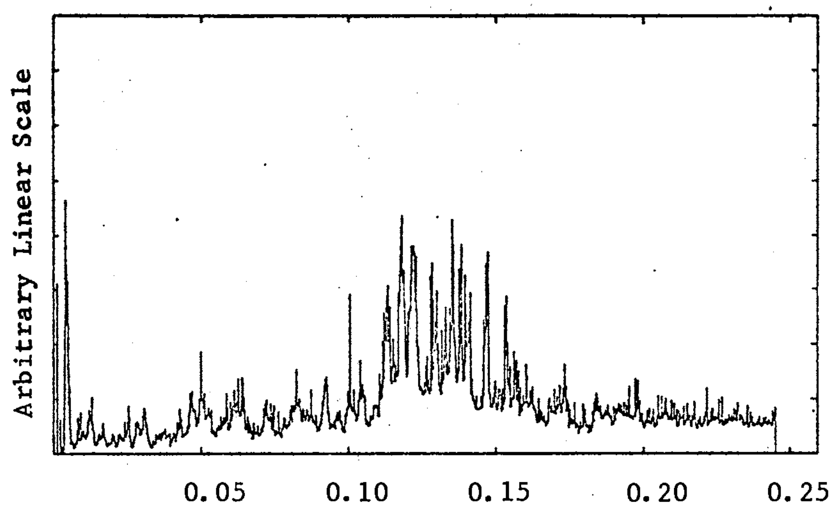


Figure 11. Orientation of acoustic and instability waves.



(a) St



(b) St

Figure 12. (a) Microphone frequency spectra D=6.35 mm, p_n/p_{ch}=1.02, Re=14,350, x/D=9, r/D=3.5,
(b) Microphone frequency spectra D=6.35 mm, p_n/p_{ch}=1.45, Re=14,350, x/D=9, r/D=3.5.

VITA ϒ

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