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SELF-EXCITED SUPERTURBULENCE: THE WHISTLER NOZZLE

William G. Hill, Jr., et al

Grumman Aerospace Corporation
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This report contans detailed experimental results for the configurations tested. It includes a discussion of several possible applications and suggestions for future experiments aimed at increasing our understanding and improving the performance of the whistler nozzle. Also included is a discussion of the relationship between the vortex

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nature of subsonic turbulent mixing layers and the differences in turbulent mixing rates for subsonic and supersonic flows.

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SELF-EXCITED SUPERTURBULENCE: THE WHISTLER NOZZLE

by

William G. Hill, Jr.

and

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Fluid Dynamics

October 1974

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Charles E. Mack, Jr.
Director of Research

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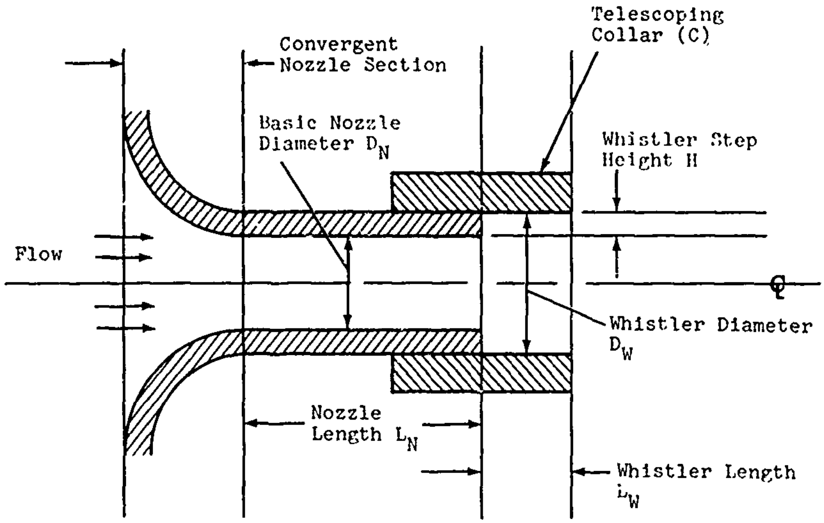
INTRODUCTION

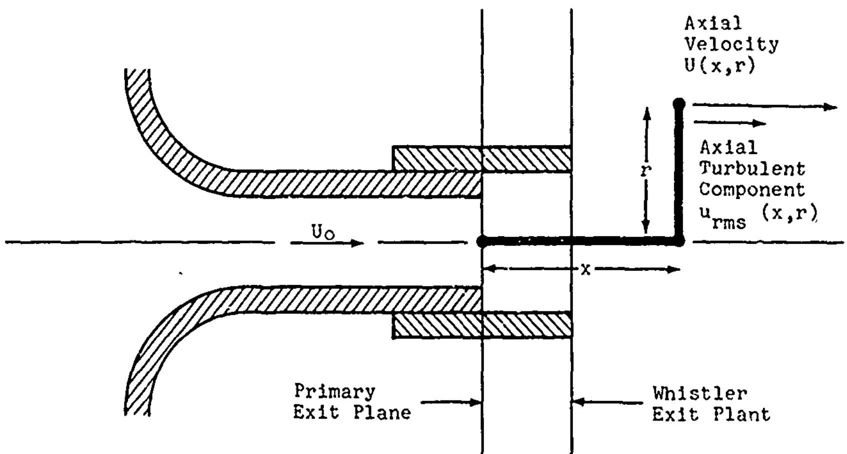
During the course of our investigations of the factors influencing jet mixing rates, we discovered a device that we call the whistler nozzle, which greatly increases jet mixing rates. The basic whistler nozzle configuration consists of a convergent nozzle, a constant area section, and an abrupt backstep (Fig. 1). The geometries used were axisymmetric; the proper length required to produce the resonant behavior (L_N in Fig. 1) for a given step height (H) was determined experimentally by sliding a collar (C) over the basic nozzle cylinder. Exact geometric location is not critical (the collar can be moved several hundredths of a diameter without destroying the process). Rectangular nozzles with an aspect ratio up to about three have also been tested, but a purely planar whistler nozzle has not yet been produced.

When the proper geometry is selected, a loud pure tone is emitted and the jet mixing rate is greatly increased. Further details of our experiments are given later in this report, but qualitatively the most outstanding characteristic of the whistler nozzle is the increased mixing and turbulence level produced in the jet as it entrains the surrounding fluid.

Acoustical stimulation of a jet plume as a means of increasing entrainment is not a new idea. Crow and Champagne generated discrete frequency sound waves with a loudspeaker located upstream of their plenum chamber; by taking advantage of plenum chamber resonances, they were able to produce exit plane sinusoidal fluctuations in velocity up to 5 percent of the core velocity at specific frequencies. The whistler nozzle, on the other hand, can produce fluctuations as high as 15 percent, and it does so without external assistance. The increased mixing rate that characterizes the performance of the whistler nozzle is produced by this



(a) Geometry of Basic Nozzle



(b) Cylindrical Coordinate System

Fig. 1 Basic Whistler Nozzle

large self-excited velocity fluctuation and the way in which this fluctuation interacts with the exit-lip geometry. The basic oscillating behavior is a standing acoustic wave with open-open boundary conditions (organ-piping) in the straight length of nozzle. Generally the half-wave mode is excited, but occasionally the full-wave or full-wave and half-wave simultaneously are excited.

While our knowledge of the behavior of the whistler nozzle is not far enough advanced to allow optimum design or performance predictions for any given application, the ability to increase turbulent mixing rates so greatly suggests a number of applications. Several fluid dynamic problems of vertical- and short-takeoff (V/STOL) aircraft could benefit from increased turbulent mixing rates. The reduced size and weight of thrust augmenting ejectors that can be obtained by increasing the turbulent mixing rate has been demonstrated by Quinn. While the benefits of decreased size and weight are obvious for aircraft application, it is also likely that a lower cost will result for commercial ground-based ejectors, especially for the simple geometry of the whistler nozzle. Increased turbulent mixing rates could also contribute to improvements in the flow beneath V/STOL aircraft in ground effect, such as decreasing ground heating and erosion effects.

Another possible application is in the suppression of aircraft exhaust plume detectability. More rapid mixing of the plume with the surrounding air results in a smaller cross section of properties such as IR emission. In this application the ability to vary the plume geometry easily and apply the whistling effect only when needed, might have special importance. Jet engine combustors and chemical lasers are additional areas where the increased mixing rates hold the promise of improved performance and/or reduced size and weight. A new class of fluidic elements could be created based on the whistler nozzle. Controlled sinusoidal signals can be generated fluidically and used as a basis for AC-type or digital-type fluid systems. A movable whistler collar can be used as a mechanical-to-fluidic switch, or control jets can be used to switch the whistling behavior on and off. Many other features of the whistler behavior may lead to other fluidic concepts. In a somewhat different type of application, we plan to use the whistler nozzle phenomenon as a research tool for studying basic jet mixing and jet noise production processes.

The role that the acoustic output generated by the whistler nozzle will play in any of these applications is uncertain. We have not yet attempted to determine geometries that minimize noise while still increasing the mixing rates.

In the following sections we present detailed experimental results for the basic whistler nozz geometries that we have tested. Also included are results for various perturbations of the basic geometry. Based on our observations of the superturbulent effects in subsonic mixing we have also speculated on the origins of the differences between s ric and supersonic free turbulent mixing rates.

EXPERIMENTAL FACILITY

The results presented in this report were obtained in the Grumman Research Department Jet Mixing Laboratory. The apparatus (Fig. 2) utilizes a centrifugal fan discharging through a diffuser into a two-foot square settling chamber containing a honeycomb straightener and turbulence-damping screens. A velocity of 180 feet/second was used in most of the reported results. The nozzle consists of a one-inch diameter ASME flow metering nozzle (elliptical contour shape) followed by constant-area sections of varying length. These constant-area sections were provided for a study of the effects of the initial boundary layer on jet mixing, but they also allow us to vary the organ-pipe frequency.

Our instrumentation consisted of a constant temperature anemometer, linearizer and hot film pro[illegible] oil-filled manometers, an x-y recorder, an oscilloscope, and a digital voltmeter. Probe traversing locations were determined from the readout of a potentiometer geared to the probe support shaft (Fig. 3). The usual procedure was to run a continuous traverse at approximately 1/2 inch per minute and record the probe position and output signals (mean velocity or RMS level) directly on the x-y recorder. Frequencies were determined by overlaying the probe output with the output of a signal generator on the oscilloscope screen. In general, the results on basic jet mixing (centerline decay and jet spreading rates) that we have obtained in this laboratory have agreed well with the summary of results collected and presented by Harsha.

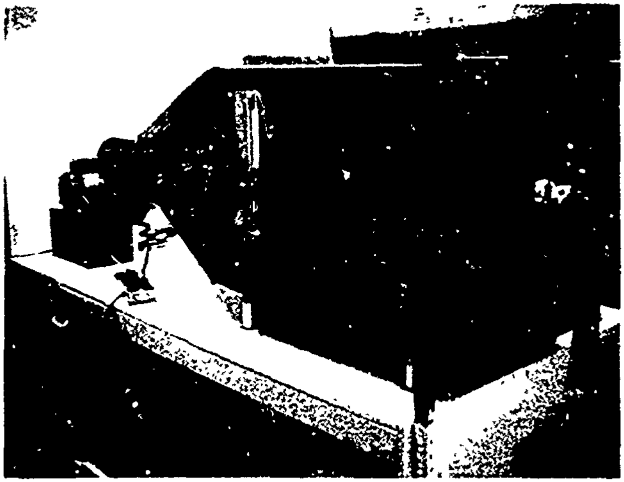


Fig. 2 Basic Jet Mixing Apparatus

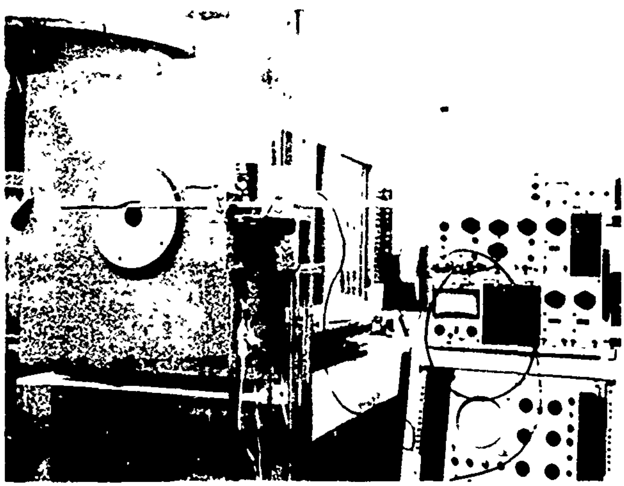


Fig. 3 Probe Traversing Mechanism

EXPERIMENTAL RESULTS

Basic Axisymmetric Whistler Nozzle Results

The original whistler nozzle was an axisymmetric nozzle having a constant area section from three to twelve diameters in length, followed by a backstep-type expansion (Fig. 1). Almost all of the quantitative data obtained to date are concerned with this basic geometry. A synopsis of the experimental results is presented below. Our investigation of other geometries has been primarily qualitative. A discussion of the results of this aspect of our work is also presented.

Quantitative data on the effects of the whistler nozzle on jet mixing have been obtained only for one-inch diameter jets. Figures 4 and 5 illustrate the basic effects of the whistler nozzle on jet mixing characteristics. The decay of velocity along our jet centerline for both the basic jet and whistler nozzle is shown in Fig. 4. These results are essentially the same as the corresponding results of Crow and Champagne, except that the whistler exhibits a more pronounced decay in axial velocity than was achieved by using a loudspeaker.

Integration of our profiles yields a variation of mass flow with axial distance very similar to that presented by Crow and Champagne. This suggests that the primary mechanisms involved in the increased mixing rates are the same. The exit velocity fluctuations couple with the superturbulence (orderly large scale vortex-ring-like structure) and lead to rapid mixing in the initial regions of the jet.

Crow and Champagne's interpretation of their data indicates that the mixing characteristics of acoustically forced subsonic jets are sensitive to two frequencies: those characterized by the

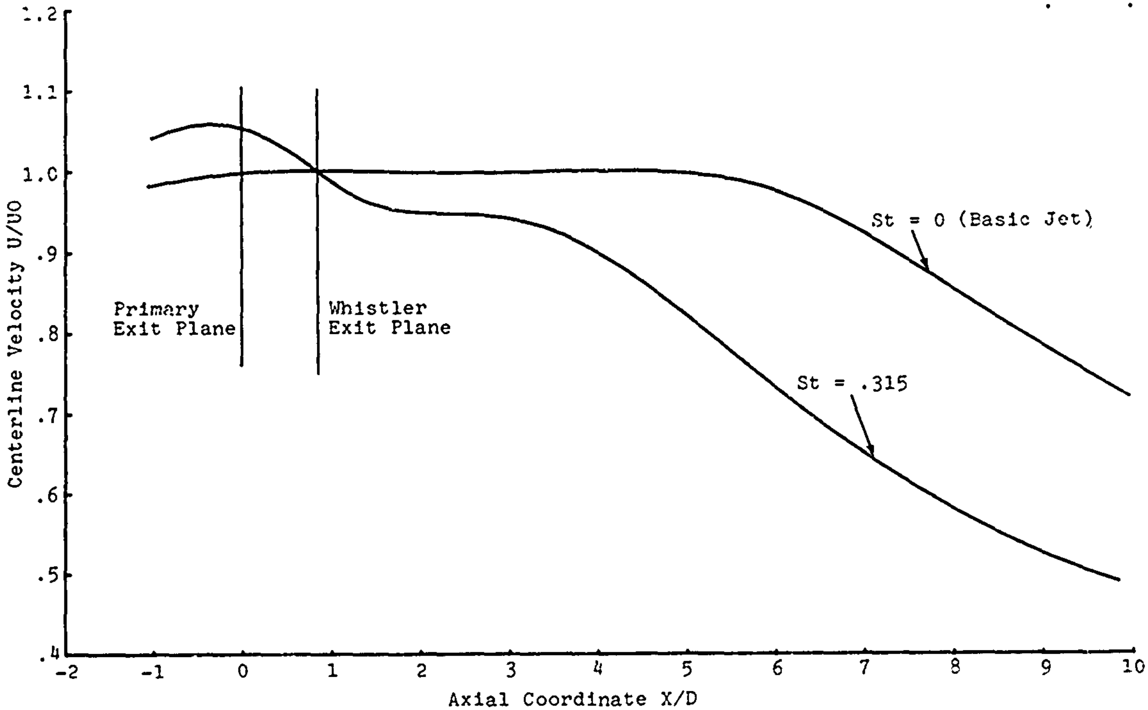


Fig. 4a. Whistler Nozzle Effects on Jet Mixing (Centerline Velocity Decay)

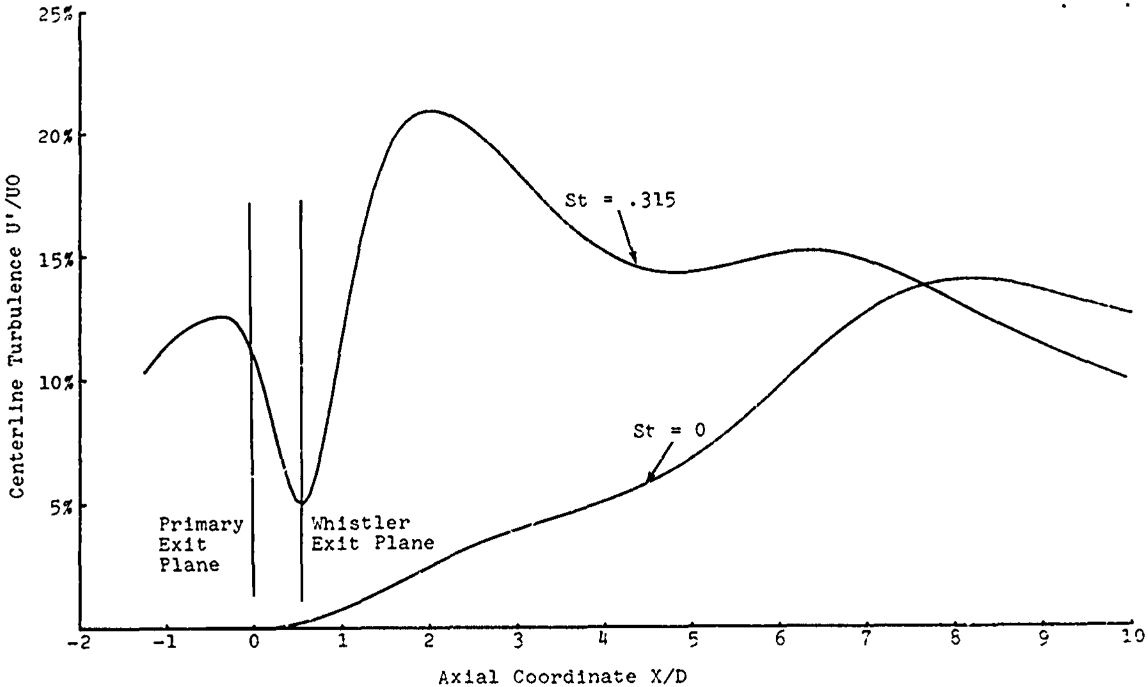


Fig. 4b Whistler Nozzle Effect on Jet Mixing (Centerline Turbulence Level)

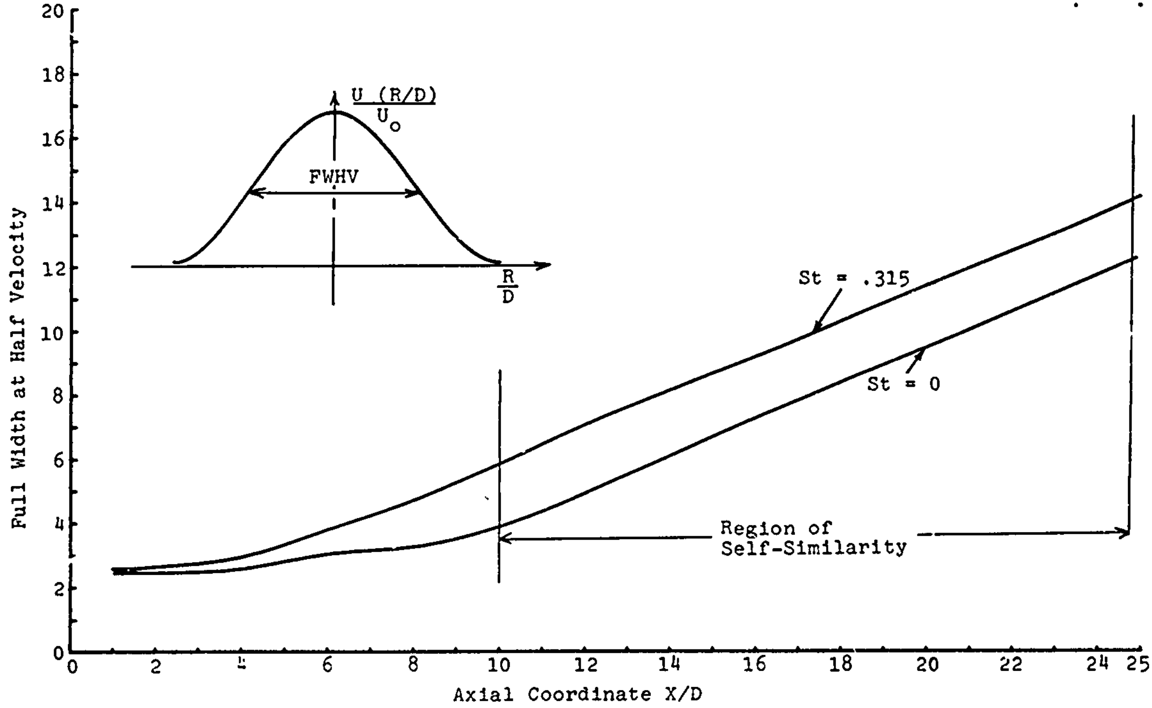


Fig. 4c. Whistler Nozzle Effect on Jet Mixing (Jet Spreading)

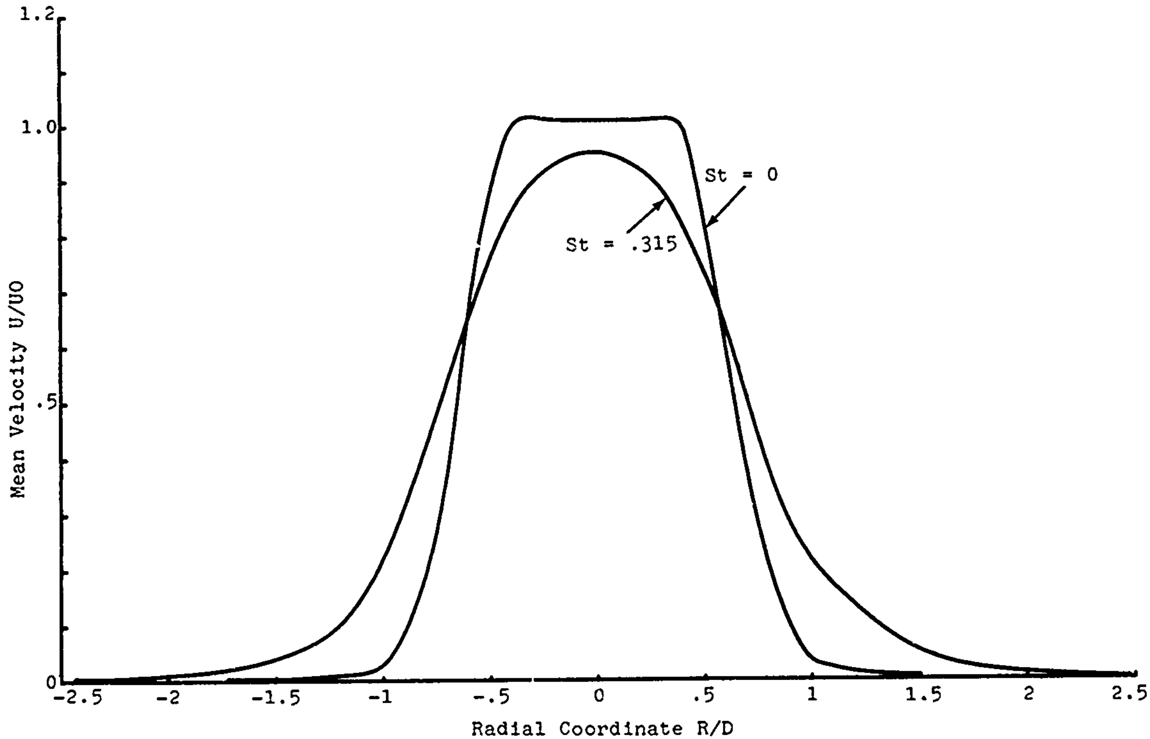


Fig. 5a. Effect of Whistler Nozzle on Radial Profiles (X/D = 2)

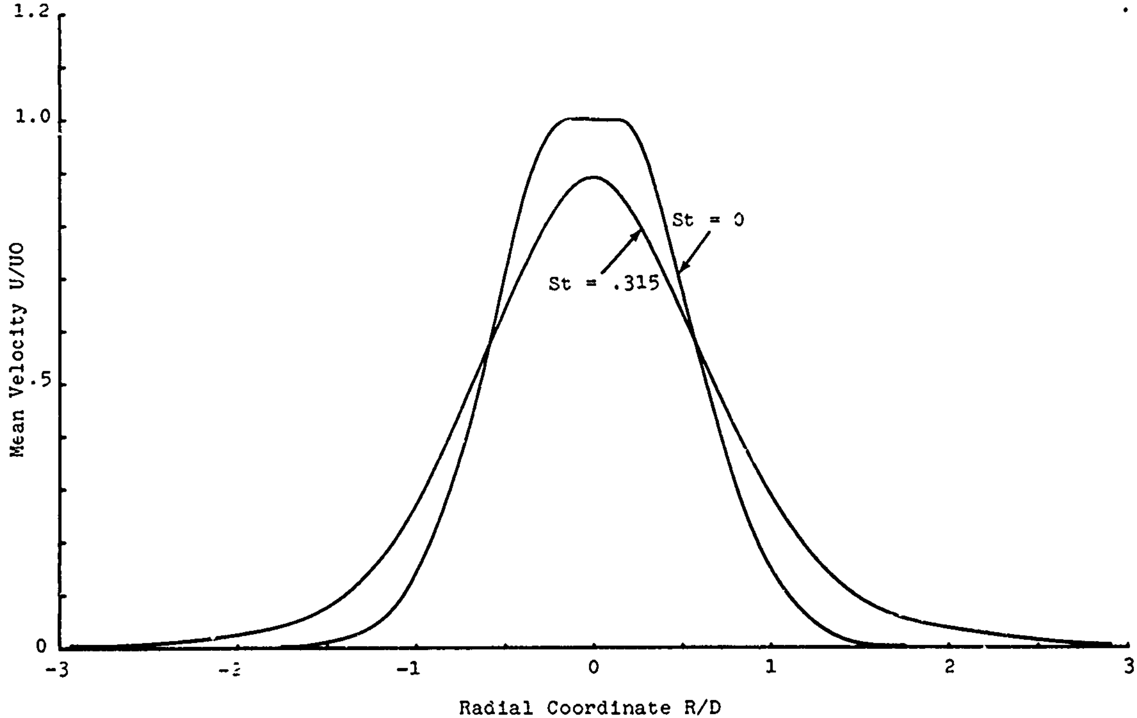


Fig. 5b. Effect of Whistler Nozzle on Radial Profiles (X/D = 4)

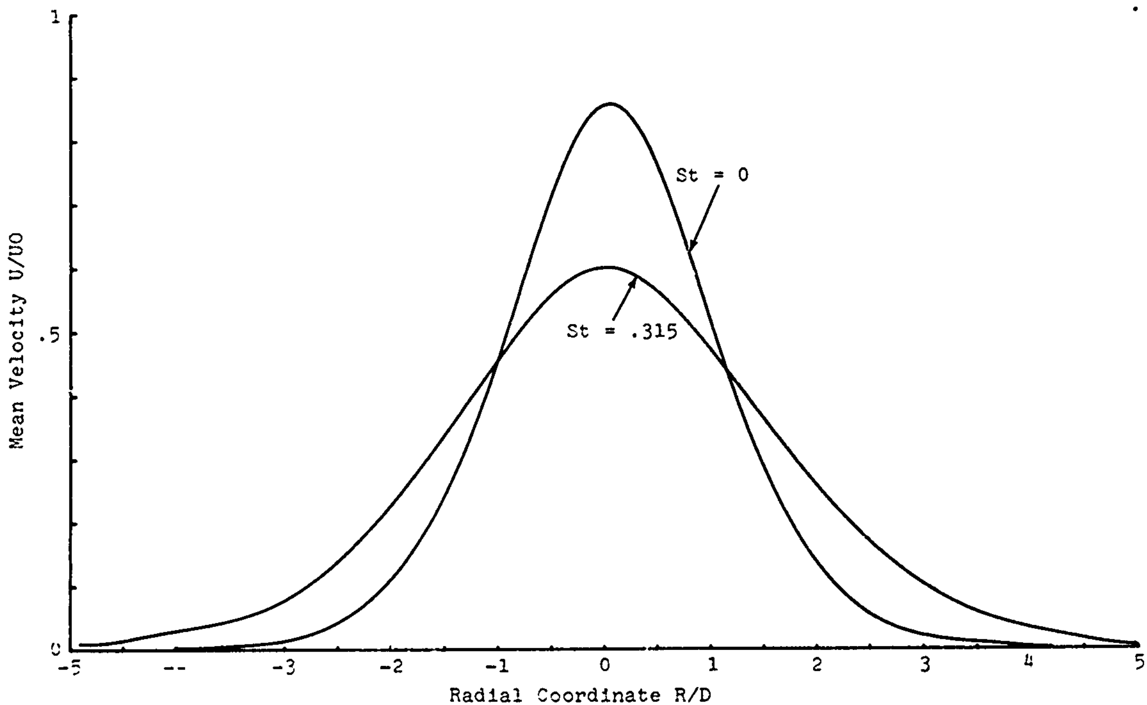


Fig. [illegible] Effect of Whistler Nozzle on Radial Profiles (X/D = 8)

Strouhal numbers $St \equiv \frac{fD}{U} = 0.3$ and 0.6. However, it is particularly difficult to summarize with a single parameter the mixing behavior of an entire jet plume under conditions of augmented mixing. Simplified means of describing the mixing behavior of a jet that are often used include:

- Axial plot of the full width at half velocity (FWHV)
- Axial plot of centerline velocity
- Axial plot of mass flux
- Axial plot of entrainment rate
- Length of potential core
- Axial shift of the virtual origin of the full jet similarity region

Crow and Champagne, however, chose the centerline velocity at four diameters downstream as the parameter to characterize the mixing response of the jet to various excitation amplitudes and frequencies. It appears from our data that this choice is an oversimplification that leads to erroneous conclusions about the mixing response of the jet plume as a whole in the forced case. Our research with the whistler nozzle has shown that the near region of the jet $\left(0 < \frac{X}{D} < 6\right)$ is particularly sensitive to acoustic forcing, and often exhibits rather unusual behavior. Figure 6 is a graphic illustration of how one's conclusions about the mixing of a jet are dependent upon the particular axial observation station. At four diameters downstream (Crow and Champagne's observation stations) the forcing at $St = 0.338$ produces the greatest change in velocity; at two diameters $St = 0.553$ produces the largest change of the three; at seven diameters the $St = 0.463$ produces the largest effect. Using the virtual origin shift as a measure of enhanced mixing rate, rather than the centerline velocity at $X/D = 4$, we <u>did not</u> observe the jet to be overly sensitive

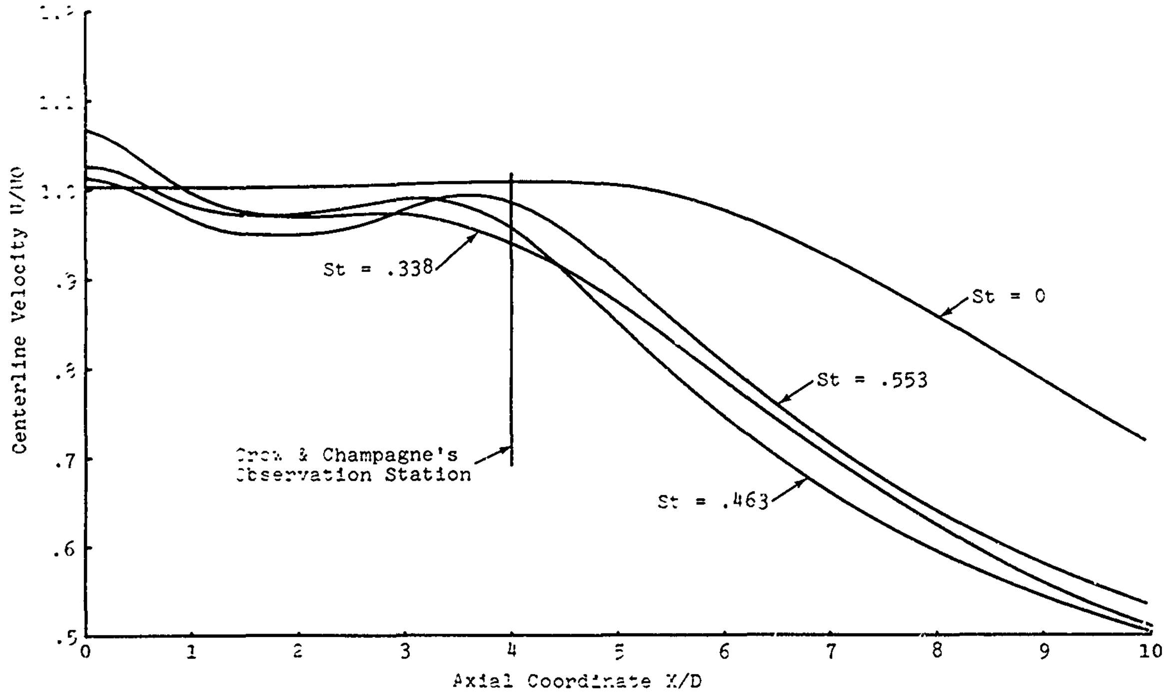


Fig. 6 Effect of Strouhal Number of Whistler on Jet Decay

at the Strouhal numbers St = 0.3 and St = 0.6; instead, the whistler seems to enhance mixing without regard to the Strouhal number over the range investigated ($0.25 < St < 0.65$). The key point is that although the local behavior (such as centerline velocity in the near field of the jet) exhibits a preferential response to forcing at certain Strouhal numbers, the gross mixing behavior is essentially independent of Strouhal number over the interval in question.

Effect of Whistler Axial Location

The basic geometry used during most of our whistler experiments consisted of a whistler section that slid over the basic straight nozzle sections. As the whistler section was extended from the nozzle exit plane, a location was reached where a loud tone was produced and enhanced mixing behavior was observed. When the whistler section was extended further the whistling stopped. However, there were often one or two further extended stations where the whistler nozzle behavior was again encountered. We designated the first position (closest to the nozzle exit) as a "first position" whistler, and successively more distant locations as "second position," "third position," etc. All data presented in other sections of this report, unless otherwise noted, are first position whistler data.

Many attempts were made at correlating the location of the whistler collar, the diameter of the whistler section, the straight nozzle length, etc. No general laws of behavior were determined. The relationships between whistler position, pipe length, and frequency are summarized in Table 1. We see no obvious relation between the oscillation mode and the collar position; the phenomenon is, however, repeatable in that the nozzle always produces the same oscillation mode and frequency for a particular collar position.

TABLE 1 RESONANT MODES OF VARIOUS WHISTLER CONFIGURATIONS

Pipe Length (In.)	First Position Frequency (Hz)	Second Position Frequency (Hz)	Third Position Frequency
3	1100 half wave	1030 half wave	none
8	680 half wave	1273 full wave	none
12	950 full wave	470 half wave	925 Hz full wave

Further experiments were then conducted to determine the effect of the second-position whistler location on mixing rates. Figure 7 shows comparisons of first- and second-position whistlers on the 8- and 12-inch pipes. A difference does exist in both cases, but again no general correlation behavior can be determined. The second-position whistler modified the behavior in the core region for both nozzles, and results in a faster mixing for the 12-inch nozzle and a slower mixing for the 8-inch nozzle. Note that in these tests a change from the first- to second-position whistler changed the frequency (and hence the Strouhal number), the RMS exit oscillation level, and the mean velocity and its gradient at the basic jet exit.

Effect of Whistler Step Height on Mixing

A series of experiments were performed to determine the effect of the step height (whistler diameter) on the mixing rates. Emphasis was placed on determining the size that produced a maximum increase in mixing rate. A second objective was to determine the minimum size that would still produce the whistler effect, since for many applications a small size could be beneficial. The results of these experiments are shown in Fig. 8. The maximum effect on centerline velocity decay and peak turbulence level is

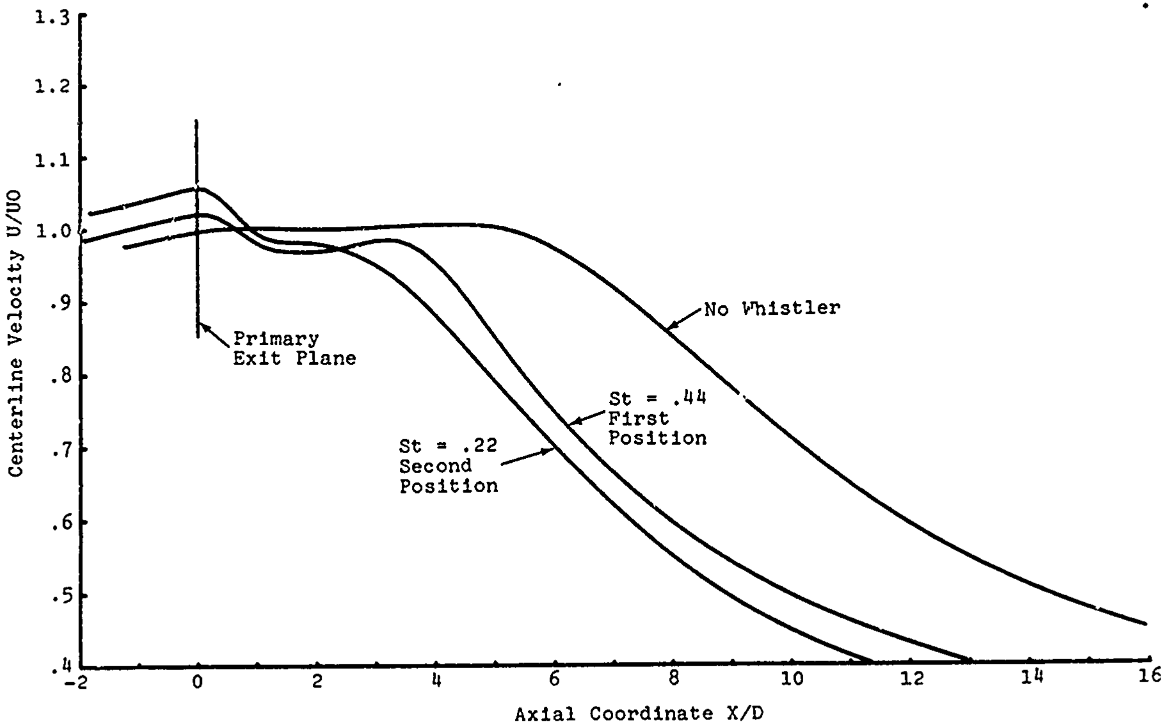


Fig. 7a. Effect of Whistler Position on Jet Decay (12-inch Pipe Length)

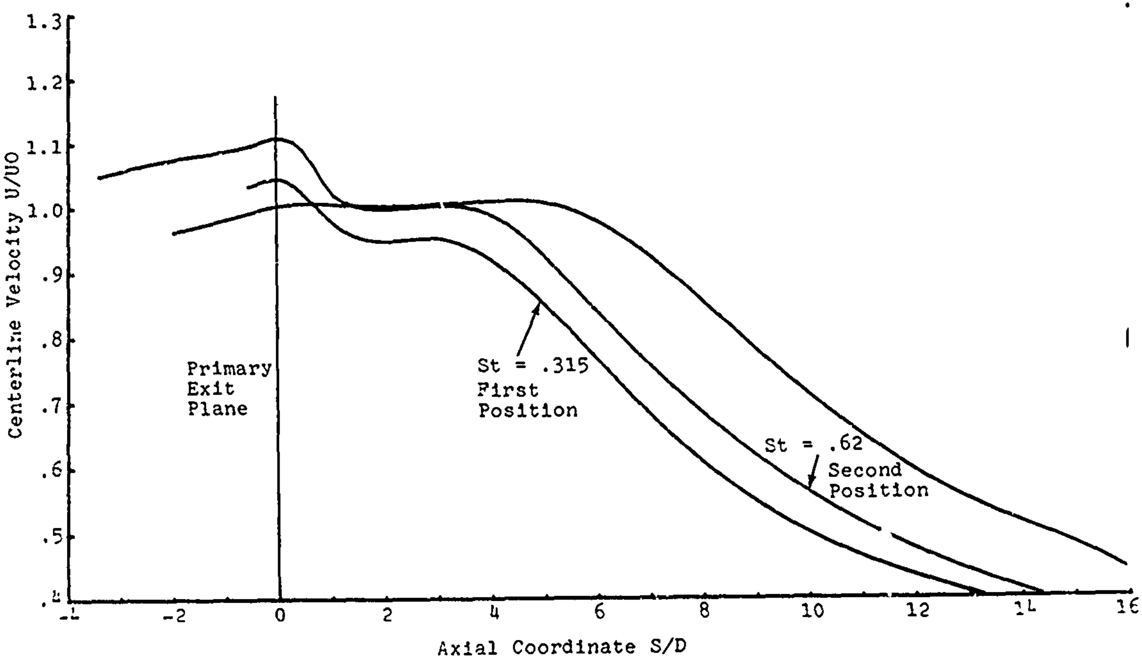


Fig. 7b Effect of Whistler Position on Jet Decay (8-inch Pipe Length)

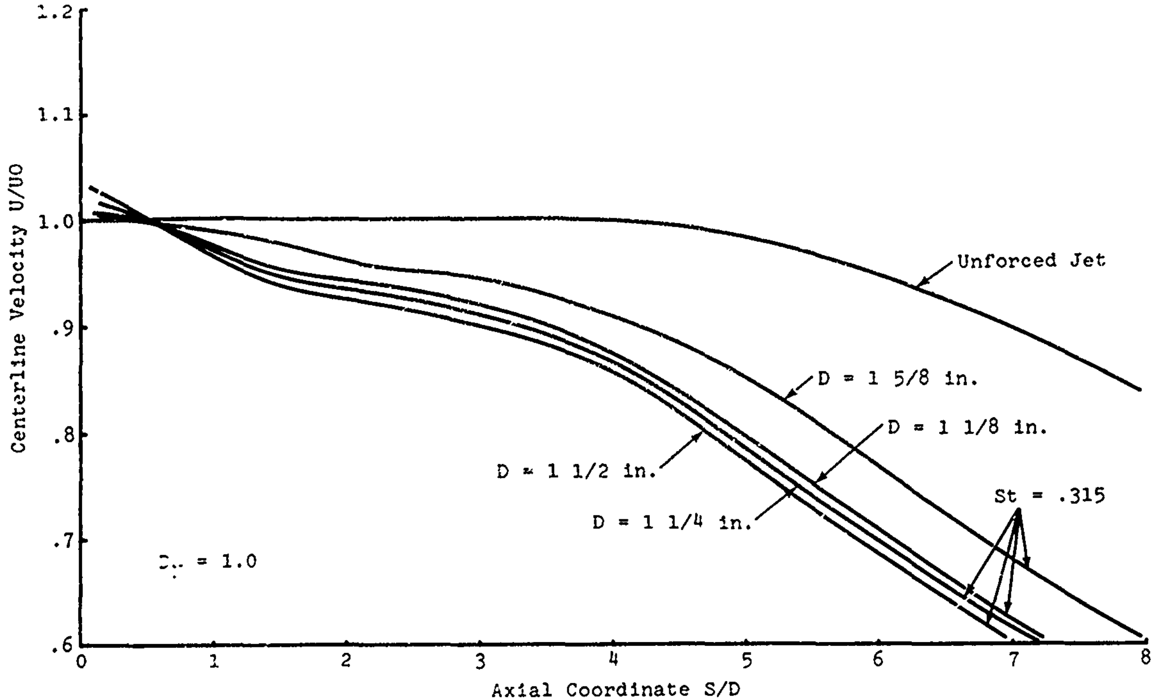


Fig. 8 Effect of Whistler Step Size on Jet Decay

produced by a 1-3/8 to 1-1/2 inch whistler diameter. A 1-1/8 inch diameter whistler, the smallest we could conveniently construct, also produced a considerable whistler effect. Since we worked only with one-inch diameter basic nozzles we do not know if the appropriate scaling parameter is D/D_o or H divided by some other length parameter such as boundary layer thickness.

Effect of Whistler on Flow Rate

It was generally observed that the centerline velocity at the exit of the basic jet was increased by operation of the whistler, but that it dropped to approximately the original (nonwhistling) exit velocity at the exit of the whistler. This resulted in large velocity gradients in some cases. Since Crow and Champagne did not measure velocity upstream of the exit, we do not know if a similar increase in mean velocity was produced in their forcing of oscillations with a loudspeaker. Examination of their plots of velocity downstream of the exit does show a gradient of centerline velocity at the exit for the forced case. Therefore, it is possible that the same general behavior occurs for this aspect of both the speaker-forced and the whistler-induced flow fields.

Effect of Initial Boundary Layer on Whistler Phenomenon

At the time these tests were being conducted, we speculated that the observed phenomenon could be connected with transition from laminar to turbulent flow in the shear layer immediately downstream of the jet exit. An experiment was therefore conducted on the 8-inch long pipe with a 1-1/4 inch whistler with and without a boundary layer trip (data of Figs. 4 and 5). The jet exit boundary layer without the trip was transitional with a thickness that was difficult to determine because of the variation in the instability waves present during transition. It was on the order of one-tenth of an inch thick and contained no high frequency components or bursts. The trip produced a turbulent boundary layer about 0.2-inch thick at the nozzle exit. The results in Fig. 9 show that there is essentially no effect of the boundary layer state on the whistler nozzle behavior.

Other Geometries

Ejector Whistler

The ejector whistler (see Fig. 10) is so named because of its similarity in appearance to a conventional ejector. This configuration was not designed to function as an ejector, however, but to relieve the low pressure occurring in the backstep region of the original whistler geometry. Reduction of this low pressure could be important for propulsion applications. The ejector whistler did work, producing almost as great an increase in mixing rates as the original whistler nozzle (Fig. 10) while at the same time relieving the low base pressure. The exit velocity for the ejector whistler is well below the exit velocity for the basic whistler; this is a direct reflection of the change in exit plane pressure. Studies of the effectiveness of this arrangement as an ejector have not been conducted.

Nonaxisymmetric Cases

We have studied square and rectangular whistler nozzles (Figs. 11 and 12), but a truly two dimensional whistler apparently will not function. Our first attempts at producing a true two dimensional whistler nozzle were unsuccessful. Subsequently, we experimented to determine the degree of axial symmetry needed to produce the whistler effect. A circular plexiglass pipe was flattened, producing a "square with round corners" exit cross section (Fig. 11). This configuration again produced the whistler

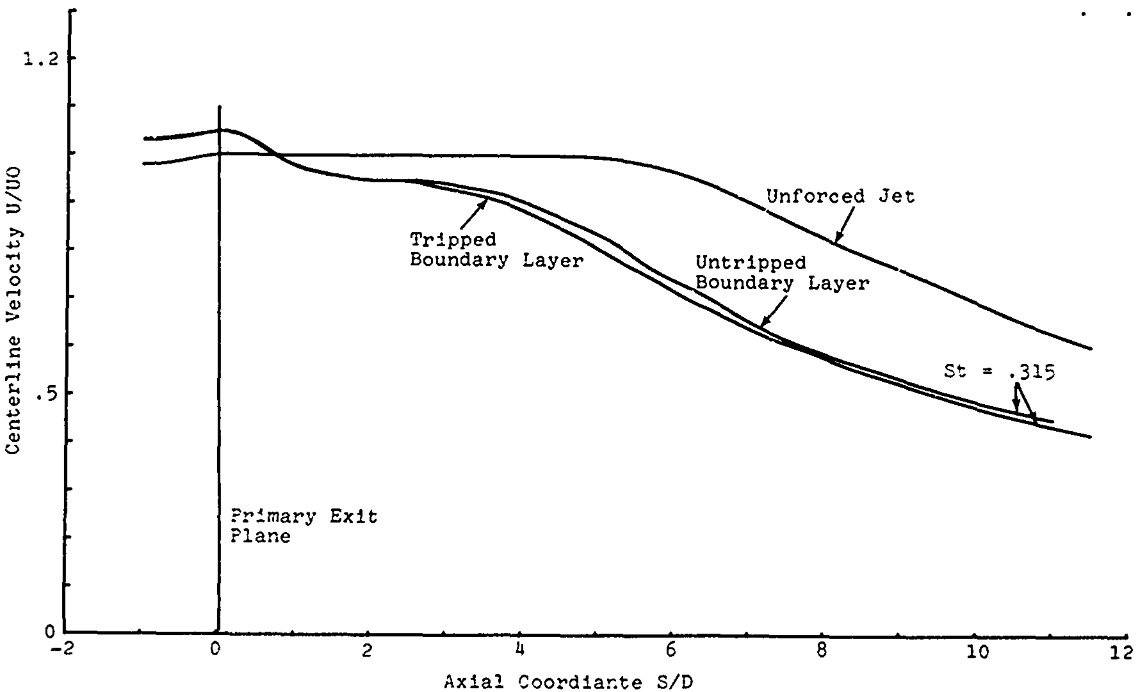


Fig. 9a. Effect of Boundary Layer on Whistler Nozzle (Centerline Velocity Decay)

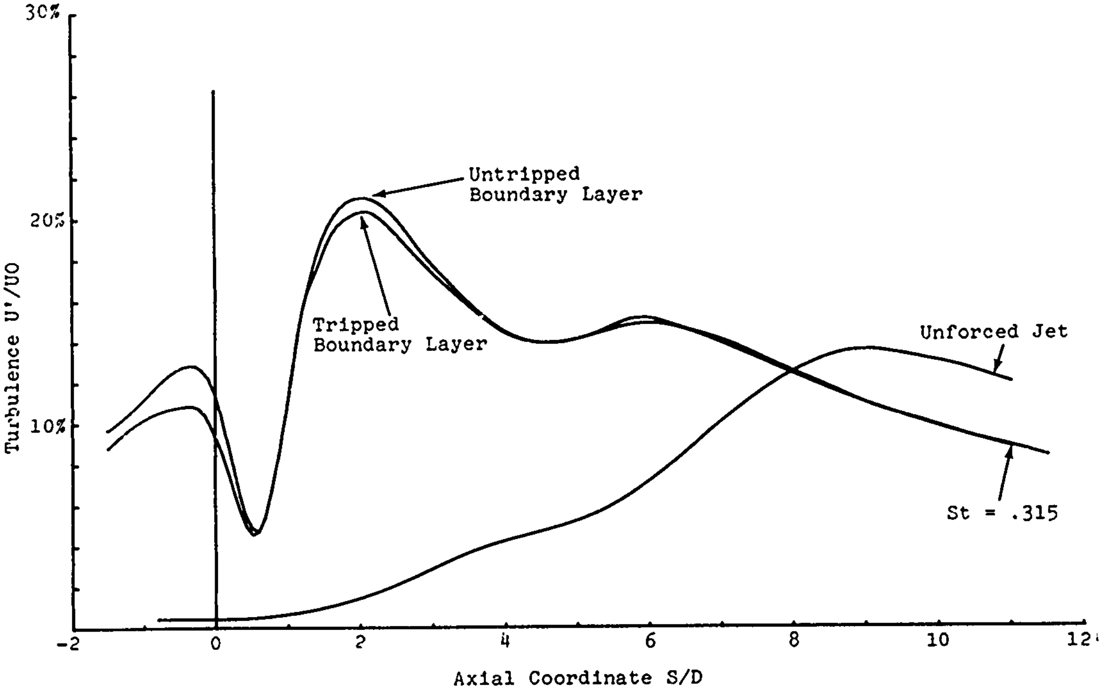


Fig. 9b Effect of Boundary Layer on Whistler Nozzle (Centerline Turbulence Level)

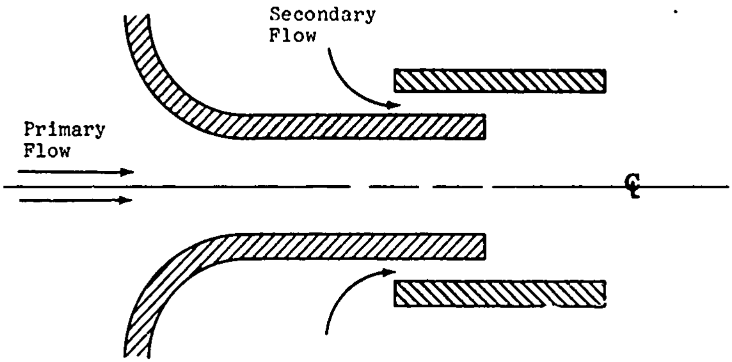


Fig. 10 Ejector Whistler

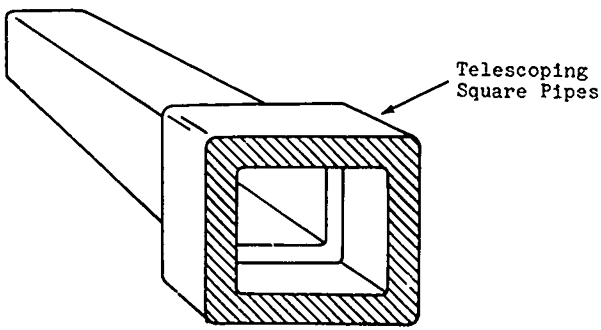


Fig. 11 Square Whistler With Rounded Corners

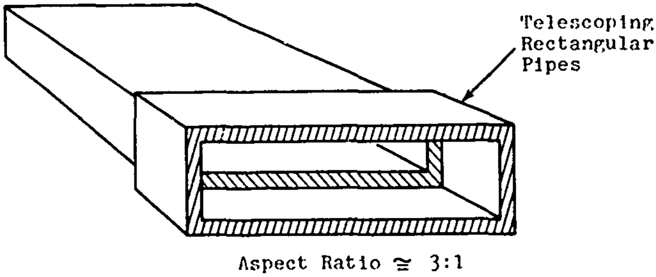


Fig. 12 Rectangular Whistler

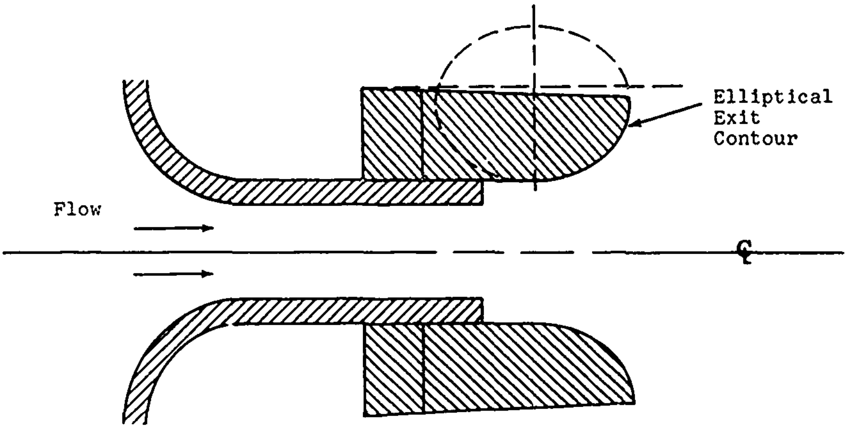


Fig. 13 Standard Whistler With Elliptically Flared Collar

behavior, using a whistler section similarly constructed. A rectangular exit nozzle was then constructed with an aspect ratio of about three (Fig. 12). This nozzle could be made to whistle when the whistler section had an outward step in all four directions. However, when the whistler section was expanded in only two opposite directions the whistling did not occur. Apparently a vortex ring effect is necessary to produce the whistler phenomenon.

Elliptically Flared Whistler

Of all the geometries tested, the elliptically flared whistler collar (Fig. 13) produced the most dramatic increase in mixing (see Fig. 14). The potential core of the jet, which in the unforced case normally extends five diameters downstream, is completely eliminated by the augmented entrainment of ambient fluid in the near-field region. Since the exit plane turbulence level of the elliptical whistler is virtually the same as that of a standard whistler, we conclude that the flared exit contour of the elliptical whistler (behaving as a diffuser) is responsible for the enhanced mixing. Further work remains to be done to determine the optimal whistler collar geometry.

Additional geometries that produced the whistler effect are the two-stage whistler (Fig. 15) and the split collar whistler (Fig. 16). No quantitative data were recorded for these configurations, but they do produce the whistler effect.

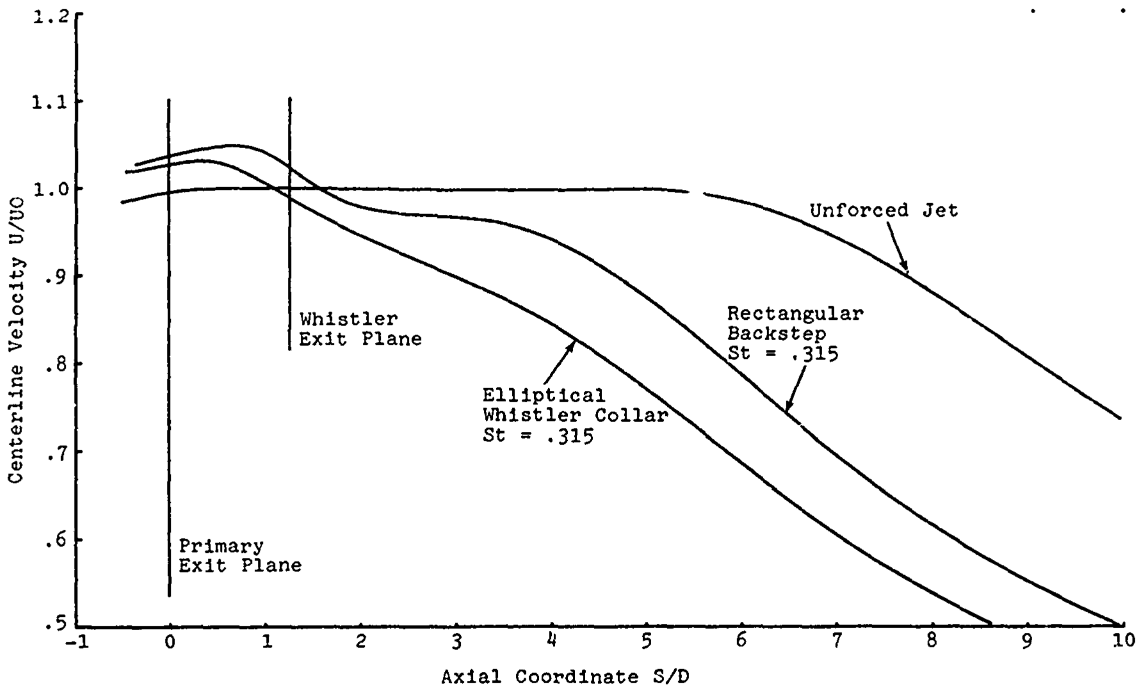


Fig. 14 Effect of Elliptically Flared Whistler Collar on Jet Decay

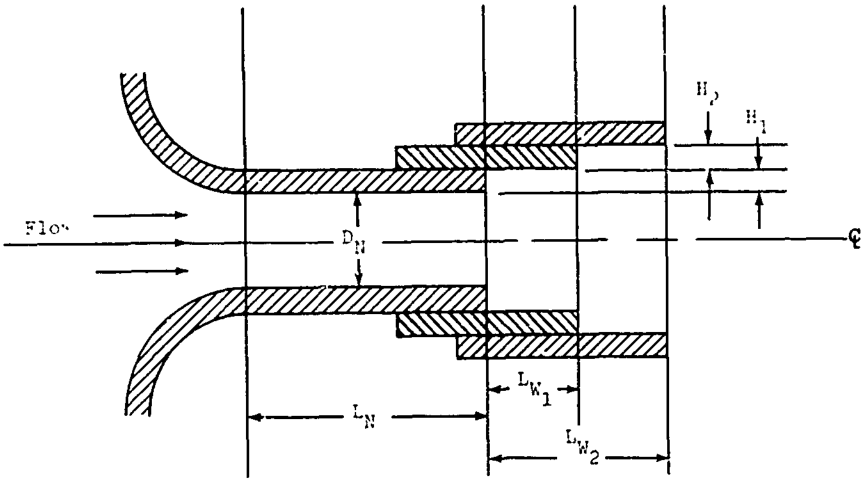


Fig. 15 Two - Stage Whistler

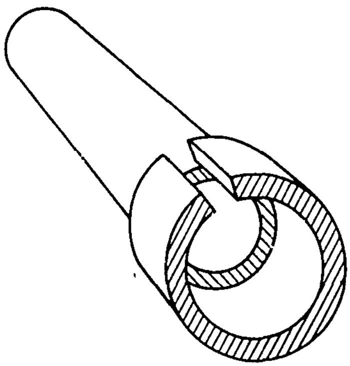


Fig. 16 Split Collar Whistler

THOUGHTS ON SUBSONIC VERSUS SUPERSONIC TURBULENT MIXING MECHANISMS

The coupling of sinusoidal oscillations in the inviscid flow with vortex-like structures in the mixing region has been noted and studied previously by Crow and Champagne. Other workers have noted the existence of these vortex-like large scale structures in the mixing zone when no outside source of excitation was present (Lau, Fisher, and Fuchs). Photographs of a similar structure were taken for the mixing of two co-flowing streams in two dimensions by Brown and Roshko. The existence of these structures even in the unforced case, and the important role they must play in determining the mixing rates, leads to an interesting speculation concerning supersonic free turbulent mixing. It has been recognized for some time that supersonic free mixing occurs at a slower rate than subsonic free mixing (NASA Langley Conference on Free Turbulent Shear Flows). It is possible that feedback from the large scale eddies to the main stream cannot occur because of the supersonic velocity. The large scale oscillations are therefore diminished or nonexistent in the supersonic case. While ample evidence of the existence and importance of the large scale structure exists for subsonic flow, we know of no data concerning its existence in supersonic flow. Such information will be difficult to obtain. The most promising approach appears to be a short duration schlieren photograph, but the high velocity will most likely require a pulsed laser light source (nanosecond times) rather than the usual spark or arc lamp flash (microsecond times).

CONCLUSIONS AND RECOMMENDATIONS

The most important feature of this investigation is the existence of the whistler nozzle phenomenon. The ability to obtain increased mixing rates without a loudspeaker or similar active input device opens many possibilities for application to large scale engineering devices (such as aircraft exhaust plumes). A feature of the observed behavior that also contributes to possible applications is the fact that many variations of the basic geometry can be made while still producing the whistler effect. The role that the noise it generates will play in applications is not known at present.

The correlation of the observed whistler nozzle frequencies with the ideal organ pipe frequencies seems to verify the basic oscillation character. In addition, we have performed measurements of the RMS velocity levels inside the straight section of the nozzle (Fig. 17) which also support this model of the behavior.

One conclusion that arises from the organ-piping aspects of the whistler nozzle is that this effect apparently cannot be produced with a sonic or supersonic nozzle exit velocity. Even though this argument is plausible, the value of applying the whistler nozzle to aircraft with sonic exit flow conditions suggests that attempts to cause a sonic jet to whistle are worthwhile. It is possible that the acoustic oscillations could be produced in a constant area subsonic passage upstream of the final sonic exit plane and still result in increased jet mixing.

Another area important for future investigation is to gain an understanding of the excitation process that occurs at the whistler lip. At present, we think that a separation-reattachment cycle in

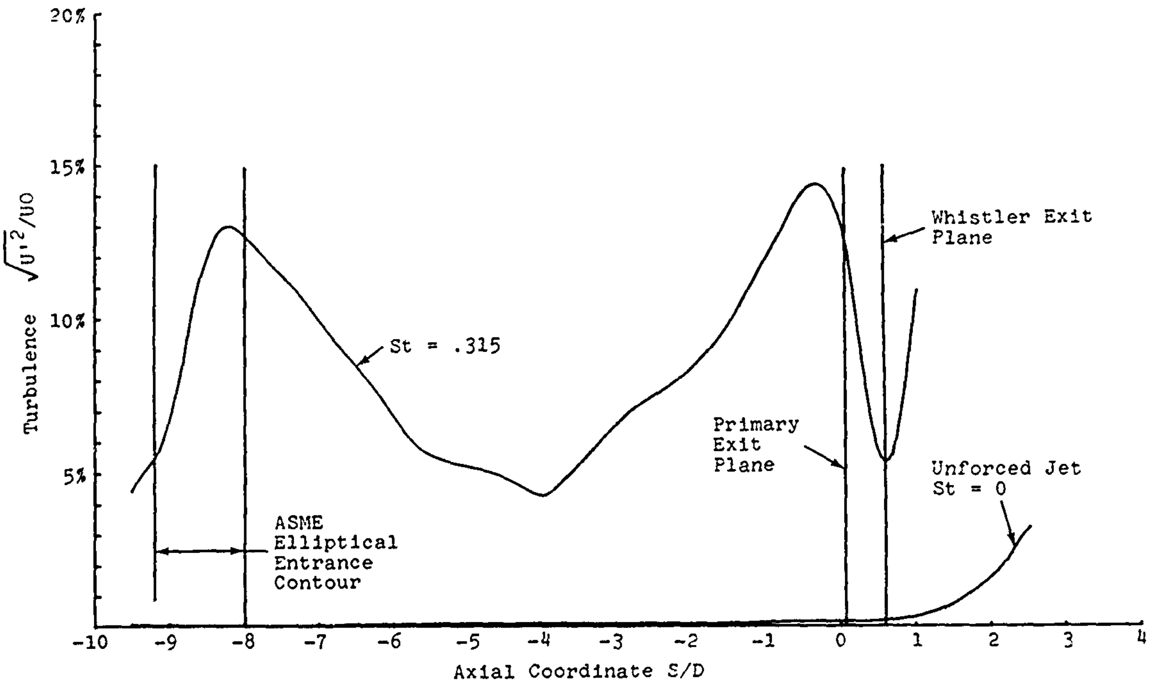


Fig. 17 Forced Oscillations Inside Whistler Nozzle

the lip region couples with the organ-pipe oscillation. The details and scaling laws of this behavior deserve further study. The inability to produce a two dimensional whistler nozzle is almost certainly coupled with the excitation process at the lip. This phenomenon also warrants future study.

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