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Preliminary Analysis of Tone-Excited Two-Stream Jet Velocity Decay

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NASA

PRELIMINARY ANALYSIS OF TONE-EXCITED

TWO-STREAM JET VELOCITY DECAY

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SUMMARY

Acoustic research related to jet flows has established that sound, by amplifying the naturally occuring large-scale structures in turbulent shear layers, can cause a more rapid decay of the jet plume velocity and temperature and an increase in jet spreading rate. One possible application of this sound-flow interaction phenomenon is to future STOL aircraft that may require modified jet plume characteristics in order to reduce the loads and temperatures on the deflected flaps during take-off and landing operations. A preliminary analysis is made herein of the tone-excitation effect on the velocity decay of model-scale, two-stream jet plumes. Measured data are correlated in terms of parameters that include excitation sound level and outer-to-inner stream velocity ratio. The effect of plume tone-excitation on far-field jet noise is examined briefly and its implication for large-scale two-stream jets is discussed.

INTRODUCTION

The acoustic control of aerodynamic flows, specifically shear and boundary layers, has become a research activity for numerous aircraft applications. The flows being studied include boundary layers over external aircraft surfaces for improved lift, reduced drag and enhanced maneuverability and stall characteristics (refs. 1 and 2). Internal flow control applications include combustors (ref. 3). Finally, the control of jet exhaust plume characteristics (refs. 4 to 8) becomes important for such applications as blown-flap STOL aircraft (C-17) for which modification of the jet plume can reduce the jet impingement velocity and temperature on the deflected flap system permitting lighter weight structures and improved aerodynamic performance. The present paper is concerned with the last application, i.e. the modification of jet plume by acoustic excitation.

In general, jet plumes can be modified by controlling (organizing) the large-scale coherent structures in the jet shear layer. In principle, an imposed high intensity tone or broadband sound excites and phase-locks with the large-scale structures occurring naturally in the jet shear layer (ref. 4), resulting in an amplification of these structures. The amplification of the large-scale structures causes the turbulence to increase with the result that the jet spreads more rapidly and the jet axial velocity and temperature decays more rapidly. The reduction of the jet core velocity and the overall increased spreading of the jet is shown schematically in figure 1 for a single-stream nozzle. Finally, the increased turbulence level associated with the excited jet results in an undesirable increase in the jet noise level (ref. 4 and 9).

At present, the most comprehensive jet plume decay data obtained with acoustic excitation are reported in reference 4. This work covers several subsonic jet Mach numbers, acoustic excitation levels, and both static and flight (free-jet simulation) conditions. All of the data were obtained with cold flow and a single-stream conical nozzle. Using a simplified empirical approach, these static and flight data were correlated in reference 5. The effect of acoustic excitation on the plume turbulence and/or far-field noise are reported in references 7 to 9; however, no velocity decay data are included in these references. Unpublished velocity decay data taken as part of the reference 7 study were obtained from the author of this reference and are included herein (ref. 10)[1].

In the present paper, a preliminary assessment and correlation of the effect of acoustic excitation on the peak velocity decay associated with essentially coplanar two-stream nozzle plumes is made. The flight data of reference 4 are analyzed as a two-stream flow system by assuming the free jet used to simulate flight effects to be the outer (secondary) stream of a two-stream nozzle. These data are supplemented by the previously unpublished conventional two-stream jet decay data of reference 10. Through the relation of the stream turbulence to the mean flow characteristics, the effect of acoustic excitation on the velocity decay of two-stream, inverted-profile nozzle plumes (refs. 7 and 8) will be discussed.

As stated previously, use of acoustic excitation to modify jet plume decay characteristics causes an increase in jet noise (ref. 4, and 7 to 9) because of the enhanced turbulence level caused by excitation of the jet shear layer. The final portion of the paper will examine the magnitude of the increased jet noise and its implication for full-size jets will be discussed briefly.

SYMBOLS

A, E   velocity ratio exponents defined in text

D   nozzle diameter

F_v two-stream velocity correlation factor

f   excitation frequency, kHz

L   acoustic excitation level, dB

M   Mach number

PWL   sound power level, dB

R   radial distance

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[1]Data furnished by Dr. C.H. Berman, formerly with the Boeing Commercial Airplane Company, now with Aero-Chem Research Labs, Inc., Princeton, NJ. Written permission to publish the data was obtained from the Boeing Commercial Airplane Co. at whose facilities the research was done.

$R_{0.5}$ radius at 0.5 velocity point

S   excitation Strouhal number, fD_1/U_1

t   static temperature

U   local velocity

u' axial component of fluctuating velocity

v' radial component of fluctuating velocity

X   axial distance downstream of nozzle exit plane

θ acoustic emission angle with respect to jet axis

Subscripts

a   ambient

c   local peak centerline

e   effective

i   inner (primary) nozzle

j   jet   at nozzle exit plane

o   outer (secondary) nozzle

R   local radial

T   threshold

FACILITIES

The test facilities in which the data used herein were obtained are briefly described in this section; further details are given in the respective references.

Lockheed (ref. 4). - The two-stream nozzle consisting of an inner nozzle with an exit diameter of 5.08 cm and an outer nozzle (free jet) having a 25.4 cm diameter is shown in figure 2. Four electro-acoustic 100 W drivers were used to excite the inner nozzle flow. The drivers were capable of being operated to ensure generation of a plane wave (0,0) mode, or a helical (1,0) mode in isolation. Far-field noise data were obtained with an array of microphones.

Boeing (refs. 7, 8, and 10). - Limited data for a low-bypass coplanar nozzle are included herein. This nozzle had an area ratio of 1.0, with a primary (inner) nozzle diameter of 8.79 cm and an outer stream nozzle diameter of

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12.45 cm. Details of other nozzles used in these studies are given in references 7 and 8. Acoustic excitation was provided by 16 acoustic drivers rated at 50 W each (8 drivers in each nozzle). Acoustic tones could be injected into the inner and outer streams independently or simultaneously. Far-field jet noise levels were obtained using an elliptic mirror.

DATA ANALYSIS

Lockheed (ref. 4). - In general, the plane wave (0,0) mode had a somewhat greater effect on the jet velocity decay than the helical (1,0) mode. However, because of the limited data available, the results from both modes are used to discuss acoustic excitation trends. It was also shown in reference 4 that a Strouhal number, S, in the range of 0.5 to 0.63 resulted in the most rapid velocity decay. Consequently, only data in this range of Strouhal numbers are used herein.

Boeing (refs. 7, 8, and 10). - Effective acoustic excitation levels (i.e., level at the nozzle exit) were not available for the data from reference 10. Consequently, only trends of the low bypass nozzle velocity decay data with acoustic excitation are discussed rather than absolute values. In reference 8, no plume velocity measurements were made. However, coupling of the use of acoustic excitation with changes in the far-field noise levels provides insight into the jet velocity decay trends, as will be discussed later.

CENTERLINE VELOCITY DECAY

A comparison of typical centerline velocity decay for a single-stream and a conventional two-stream high bypass ratio nozzle plumes (ref. 4 data) is shown in figures 3 and 4 for both unexcited and acoustically excited flows. For both nozzles, the effect of excitation is to cause a more rapid centerline velocity decay. In the range of the present data, an increase in the two-stream velocity ratio, U_o/U_1, causes a less rapid centerline velocity decay. However, an increase in the excitation level causes a more rapid centerline velocity decay with axial distance. As discussed in reference 4, the degree of change in the centerline velocity decay caused by acoustic excitation depends greatly on the excitation Strouhal number, S. In the range of excitation Strouhal numbers included herein, 0.5 < S < 0.63, only relatively small changes in the velocity decay are evident in the excited flows for this range of S values.

Limited, previously unpublished, centerline velocity decay data for a coplanar low-bypass ratio nozzle (ref. 10) is shown in figure 5 for both acoustically excited and unexcited flow. With excitation applied to both streams, a significantly more rapid velocity decay is evident. Unfortunately only the input excitation level (~140 dB) is available for these data, not the effective value at the nozzle exit. Similar limited data were obtained with a single-stream nozzle (also shown in fig. 5) and a high-bypass ratio (3) nozzle not shown in the figure. For the latter nozzle, the outer nozzle exit plane was located upstream of the inner nozzle exit so that the results cannot be compared directly with those for the coplanar exit nozzle. However, even for this high-bypass ratio nozzle, acoustic excitation caused a more rapid center-line velocity decay than that without excitation.

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Although an inverted profile nozzle was included in the reference 10 study, no acoustically excited centerline velocity decay are available. However, in reference 8 it is stated that excitation of the outer stream was more efficient, from an increased far-field noise point of view, than exciting a single-stream nozzle plume.

This observation will be examined in more detail later in the section devoted to far-field noise considerations.

Excitation Level Correlation. - According to reference 11, a minimum or threshold level of acoustic excitation exists for single-stream nozzle plumes below which the plume characteristics are not affected. This threshold level, L_T, is a function of the jet Mach number and the excitation Strouhal number, S. The analysis in reference 5 indicated that the same threshold excitation parameter was valid for both static and flight conditions. In the present analysis, it was assumed that this threshold excitation parameter was also valid for two-stream nozzle plumes. The single-stream centerline velocity decay was correlated in reference 5 through an effective tone-excitation parameter given by:

$$L_e = 1 + 2 \frac{(L - L_T)}{L_T} \tag{1}$$

which is considered valid for $(L - L_T) \geq 0$. The L_e parameter is applied as a multiplication factor to the abscissa in figure 4 yielding the following relationship:

$$\frac{U}{U_1} \propto \frac{X}{D_1 \sqrt{1 + M_1}} \left(\frac{t_1}{t_a}\right)^{0.25} L_e \tag{2}$$

The two-stream centerline velocity decay data are shown in figure 6 in terms of equation (2). It is apparent that the L_e term provides good correlation of the excited and unexcited centerline two-stream velocity decay data.

Velocity Ratio Correlation. - The data shown in figure 6 can be correlated for the nozzle flow velocity ratio, U_o/U_i, by the method of reference 12. In this reference, a velocity ratio parameter, F_v, is calculated for the range of the present data as follows:

$$F_v = 1 + \left(\frac{D_o}{D_1} - 1\right)\left(\frac{U_o}{U_1}\right)^A \tag{3}$$

where

$$A = 0.625 \left(\frac{D_o}{D_1}\right)^{0.67} \left(\frac{t_a}{t_1}\right)^{0.2} \left(\frac{t_a}{t_o}\right)^{0.5} \tag{4}$$

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The correlation of the unexcited two-stream centerline velocity decay using equation (3) is shown in figure 7 while the excited centerline velocity decay using equation (3) is shown in figure 8. It is apparent that, in general, the conventional two-stream centerline velocity decay data are normalized by the L_e and F_v parameters. However at abscissa values greater than about 6, the excited two-stream decay data appear to have a reduced slope compared to that for the single-stream and unexcited two-stream data.

In order to normalize the excited two-stream data shown in figure 8 so that it coincides more with the unexcited two-stream and single-stream nozzle curve, a dimensionless, variable exponent must be applied to either the ordinate or abscissa te m. For a general solution, the variables in this exponent must reduce to 1.0 for a single-stream jet. In the present work, it was arbitrarily decided to place this exponent on the ordinate term, U/U_1.

On the basis of the available data, the required exponent, E, for conventional two-stream jets was developed and is given by:

$$E = 1 + 0.75 \left(\frac{D_o}{D_1} - 1 \right) \left(1 - \frac{U_o}{U_1} \right)^{2.67} (L_e - 1)^{0.67} \qquad (5)$$

the results of applying the exponent, E, to the centerline velocity ratio, U/U_1, is shown in figure 9. Good correlation of the conventional two-stream jet data with the single-stream decay curve is now evident.

It should be noted that for the low-bypass nozzle of reference 10, the exponent is about 1.1 which, as expected, has only a small affect over the limited range of data available.

RADIAL VELOCITY PROFILES

It was shown in reference 6 that unexcited conventional two-stream radial velocity profiles follow the same general trends as those for a single-stream nozzle. Both single- and two-stream radial velocity profiles could be represented by the following equation taken from reference 13:

$$\frac{U_R}{U_c} = \left[1 - \left(\frac{R}{2.27 \, R_{0.5}} \right)^{1.5} \right]^{2.0} \qquad (6)$$

Unpublished NASA data indicate that the preceding equation is also valid for inverted-profile nozzle plumes (i.e., $U_o > U_1$). Finally, it was demonstrated in reference 6 that the radial velocity distribution for a single-stream excited jet plume is also given by equation (6).

For two-stream excited jet plumes, only extremely limited data are available, and that only for a low bypass nozzle with a conventional velocity profile ($U_o < U_1$). In reference 10, radial velocity profiles were made available at X/D_1 values of 1.0 and 12. These data are shown in figure 10, with and without acoustic excitation. Also shown is the single-stream curve based on equation (6) from reference 13. It is apparent that the excited two-stream radial velocity profiles are also represented by the parameters contained in

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equation (6). The deviation of the $X/D_1 = 1.0$ data from the curve at $U_R/U_C > 0.5$ is expected and typical of data in the plume core region near the nozzle exit. Further details regarding analysis of the data in this region of the plume are given in reference 12.

On the basis of the available data that includes excited and unexcited single- and conventional two-stream jet as well as unpublished data on unexcited inverted-profile jets, it is reasonable to believe that the radial velocity distribution for excited inverted-profile plumes are also expressed by equation (6).

TURBULENCE INTENSITY

Acoustic excitation of a jet plume causes an increase in the broadband turbulence as well as an effect on the mean flow (refs. 4, 7 and 9). In general, the largest increase in turbulence intensity occurs in the core region of the plume (small X/D-values) with lesser effects, even reductions, occurring in the plume mixed flow far downstream of the nozzle exit.

Typical examples of the effect of acoustic excitation on the turbulence intensity in a conventional two-stream jet plume are shown in figures 11 and 12. It should be noted that the turbulence intensity data shown in these figures are strictly representative of the nozzle and flow conditions used in reference 4; however, the trends shown are believed representative of all conventional two-stream nozzle plumes.

Centerline Turbulence Intensity

The centerline turbulence intensity, $\sqrt{\overline{u'^2}}/U_1$, is shown in figure 11 for the large diameter ratio nozzle of reference 4.

Velocity Ratio Effect. - At a fixed acoustic excitation level (fig. 11(a)), the peak turbulence intensity at $X/D_1 < 5$ remains nearly constant with an increase in the two-stream velocity ratio, U_0/U_1. However, the peak value of the turbulence intensity shifts increasingly farther downstream with increasing velocity ratio. In the mixed flow region, the peak turbulence intensity point also shifts downstream with increasing velocity ratio, but more important the entire level of the turbulence intensity is significantly reduced in the region of $6 < X/D_1 < 14$. Beyond an X/D_1 of 14, there is little change in the turbulence intensity.

Excitation Level Effect. - The effect of acoustic excitation level on the centerline turbulence intensity is shown in figure 11(b). In general, the turbulence intensity increases markedly near the nozzle exit ($X/D_1 < 10$) but decreases slightly at $X/D_1 > 14$.

Radial Turbulence Intensity

The typical effect of acoustic excitation on the radial component of turbulence intensity, $\sqrt{\overline{v'^2}}/U_1$ is shown in figure 12. With acoustic excitation, the turbulence intensity is increased for R/R_1 values less

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than 0.8. In the region of the inner nozzle lip line ($R/R_1 \sim 1.0$), little increase in turbulence intensity was measured; however, the peak turbulence intensity was shifted to a somewhat higher R/R_1 value indicating that the excited jet spread had increased relative to that for the unexcited jet.

FAR FIELD NOISE CONSIDERATIONS FOR EXCITED JETS

In references 4, 7, 8, and 14, the effect of acoustically excited jets was shown to increase the far-field noise level. This increase is reflected in both spectral and overall noise measurements. Typical sound power levels for single-stream and two-stream jets are shown in figure 13 for both unexcited and excited states (ref. 4). In general, excitation increases the noise levels over the entire frequency range. The excitation tone is readily apparent as are harmonics of the tone.

By interpreting the flight-to-static noise amplification data for excited flows (ref. 4) as two-stream to single-stream noise amplification, it is apparent from figure 14 that essentially the same noise amplification due to acoustic excitation is obtained with or without the secondary stream.

In figure 15, the excess noise (amplification) is shown as a function of the effective excitation input, $L-L_T$. The data shown are taken from references 14, 4, and 8 for U_0/U_1 ratios of 0 (single stream), 0.18 and 0.5, respectively. The data were obtained using internally mounted acoustic drivers to provide the flow excitation. While the data are limited and agreement between the three sets may even be fortuitous, the data nevertheless indicate the trend of excess noise amplification with acoustic excitation level.

The highest excitation level used in reference 4 was about 143 dB. This caused relatively small changes in the two-stream centerline velocity decay. In order to achieve significant velocity decay modifications, excitation levels of the order of 170 dB may be needed (ref. 15). For such a case, the jet excess noise amplification, extrapolated from figure 15, would be of the order of 12 dB. It is obvious that further work is needed to verify such an extrapolation of the present available data and, in addition, include jet temperature, higher (supersonic) velocity and full-scale nozzle effects.

With respect to scaling effects, some insight for jets can be gained by examining the scaling trends for excited airfoils (ref. 2) and slit jets and orifices (ref. 16). Both references show that an increase in component sizes requires an increase in the acoustic excitation level in order to achieve the same desired change in the flow field. Consequently, large-scale experiments are needed in order to establish the acoustic excitation levels required to achieve specific changes in jet plumes.

INVERTED-PROFILE VELOCITY DECAY ASSESSMENT
FROM TURBULENCE AND NOISE MEASUREMENTS

A qualitative assessment of the inverted-profile two-stream velocity decay benefits that might be achieved by acoustic excitation can be made by considering all the data presented in references 4, 7, 8 and 10. Acoustic excitation causes a more rapid mean velocity decay and greater jet spreading. These plume modifications are accompanied by an increase in the small-scale turbulence

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levels and in the far-field noise levels. As stated previously, the increase in turbulence level is attributed to the excitation enhancement of the large-scale coherent structures in the jet shear layer. At the same time the increase in small-scale turbulence level, perhaps coupled with that of the large-scale structure, causes an increase in the noise emitted by the jet. It is reasonable, then, to assume that measurements of turbulence and/or noise levels provide an indication of what is happening to the mean flow. Thus, it can be assumed that increases in turbulence and/or noise levels are associated directly with a more rapid velocity decay and increased jet spread.

In reference 7, it was shown that both turbulence and noise levels were increased when the inverted-profile nozzle plume was acoustically excited. On the basis of the premises discussed previously, it is reasonable to assume that the velocity decay for the inverted-profile nozzle plume was increased by acoustic excitation. It remains to be determined by how much the mean flow for such nozzles is modified by acoustic excitation. It can be speculated that because the outer stream for such a nozzle configuration is thin that acoustic excitation could provide a very substantially increased plume velocity decay.

CONCLUSION

From the present analysis of limited coplanar two-stream, unexcited and excited jet plume data the following preliminary conclusions can be made:

1. The centerline velocity decay for excited, conventional two-stream jets becomes increasing more rapid with increasing levels of acoustic excitation.

2. Preliminary empirical correlation equations for conventional two-stream nozzle plumes were developed that take into account the velocity ratio between the streams and the acoustic excitation level.

3. From consideration of the effects of acoustic excitation on the plume turbulence intensity and acoustic signature, it is reasonable to expect that inverted-provide nozzle plumes also will exhibit more rapid velocity decay characteristics when acoustically excited.

4. For large changes in the velocity decay, acoustic excitation of jet plumes will cause significant broadband noise level increases in the far-field.

5. Acoustic excitation appears to be an effective means by which the exhaust plume velocities, and consequently temperatures, impinging on the deflected flap system for STOL aircraft can be reduced.

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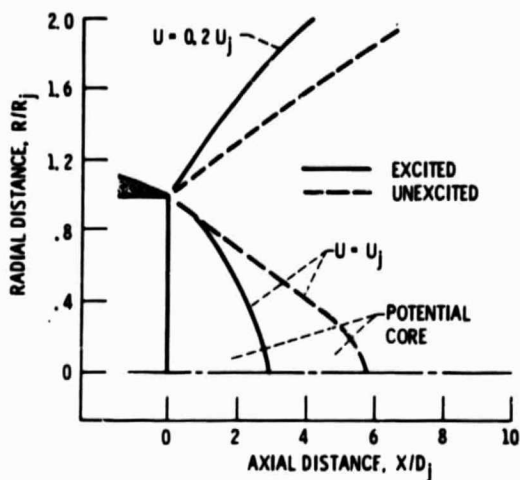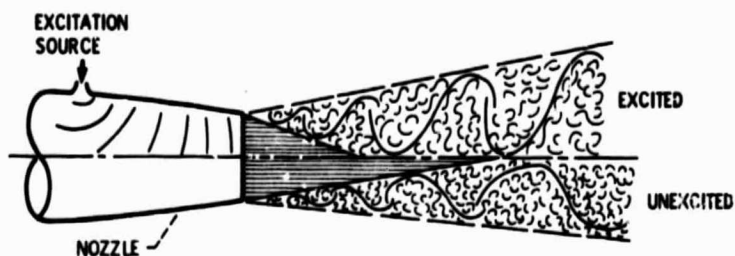
Figure 1. - Jet mixing enhancement by upstream acoustic excitation.
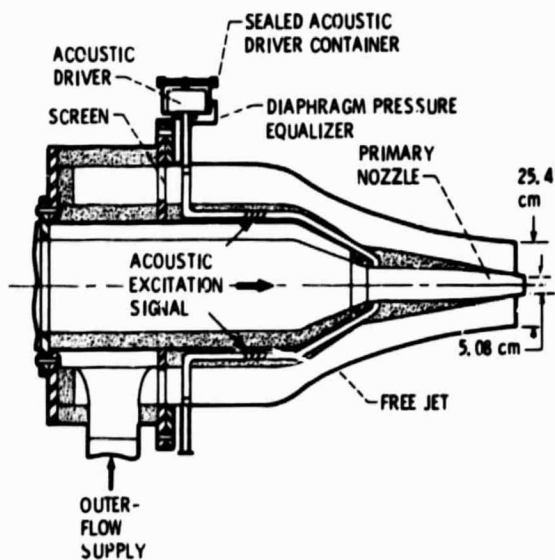
Figure 2. - Flow excitation facility (Ref. 4).
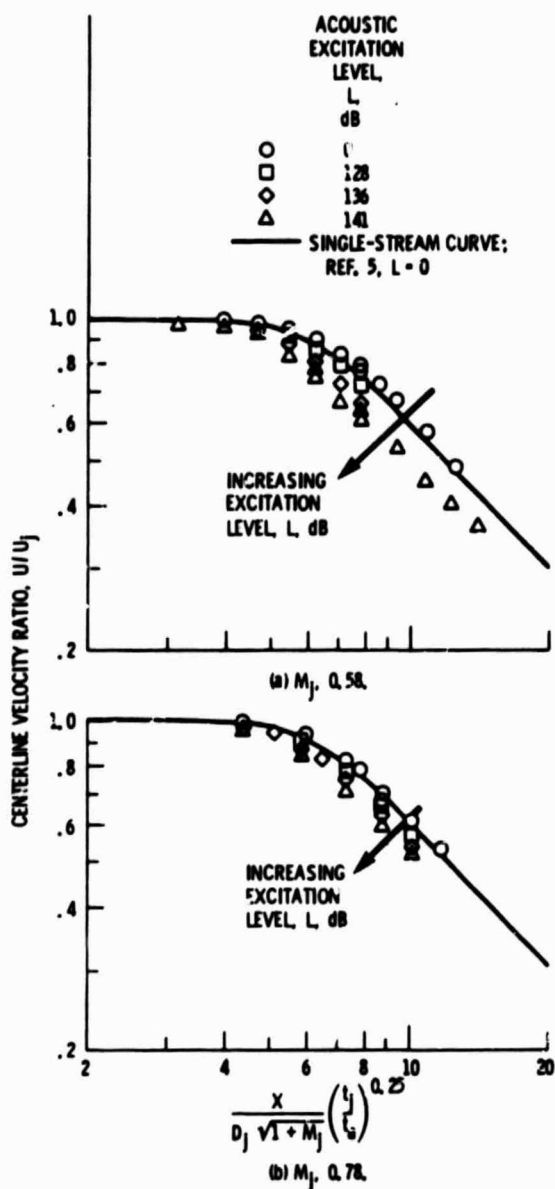
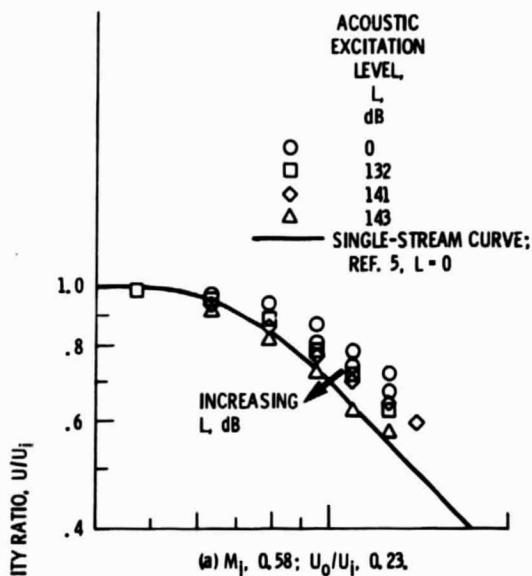Figure 3. - Effect of acoustic excitation on single-stream centerline velocity decay (Ref. 4).
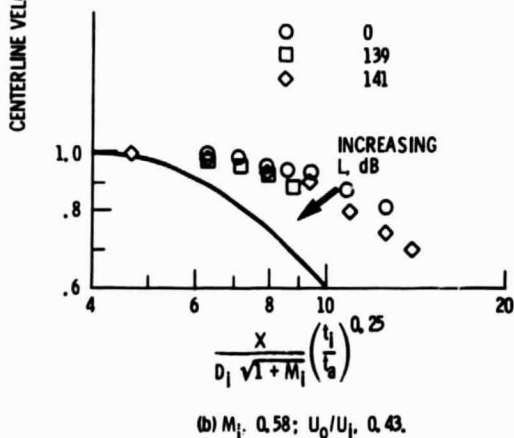
Figure 4. - Effect of acoustic excitation on conventional two-stream centerline velocity decay (Ref. 4).
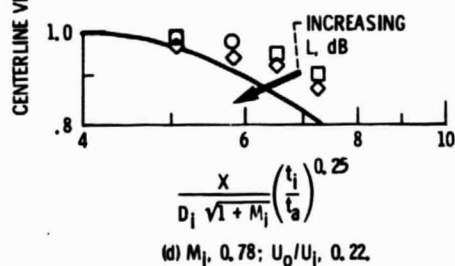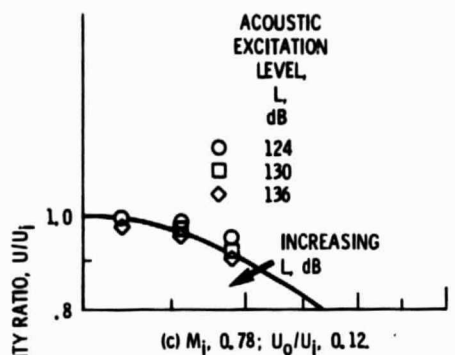
(c) M_j, 0.78; U_o/U_j, 0.12.

(d) M_j, 0.78; U_o/U_j, 0.22.

Figure 4. - Concluded.
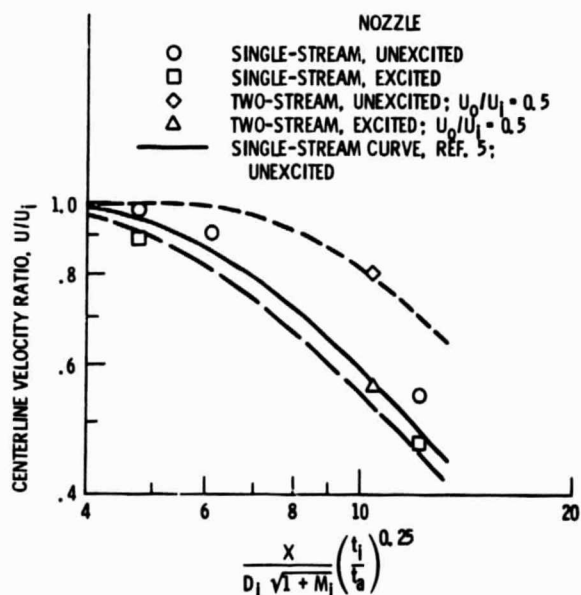
Figure 5. - Comparison of unexcited and excited single-stream and two-stream nozzle velocity decay (Ref. 10). U_j, 122 m/s; input acoustic excitation level, 140 dB.
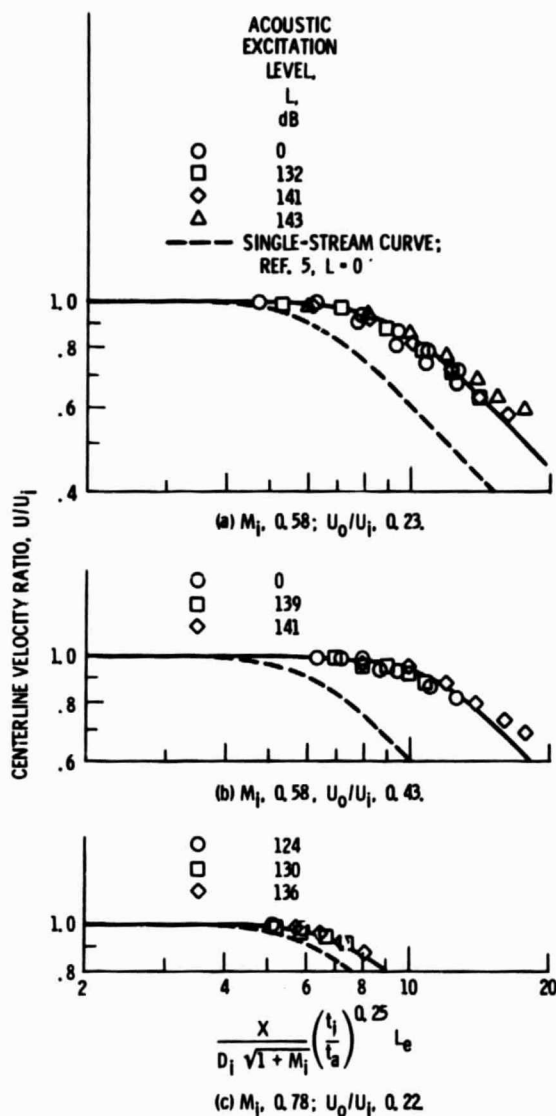
Figure 6. - Correlation of centerline velocity decay for two-stream jet plumes, with and without acoustic excitation (Ref. 4 data).
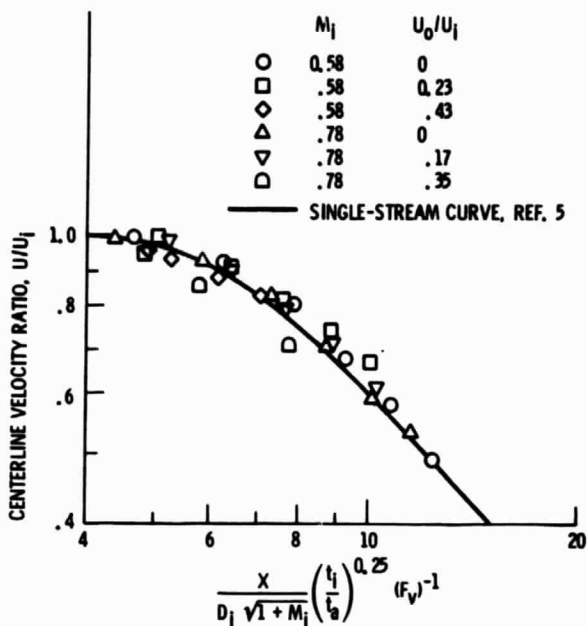
Figure 7. - Correlation of unexcited two-stream centerline velocity decay using velocity ratio parameter F_v from Ref. 12.

(a) M_i, 0.58.
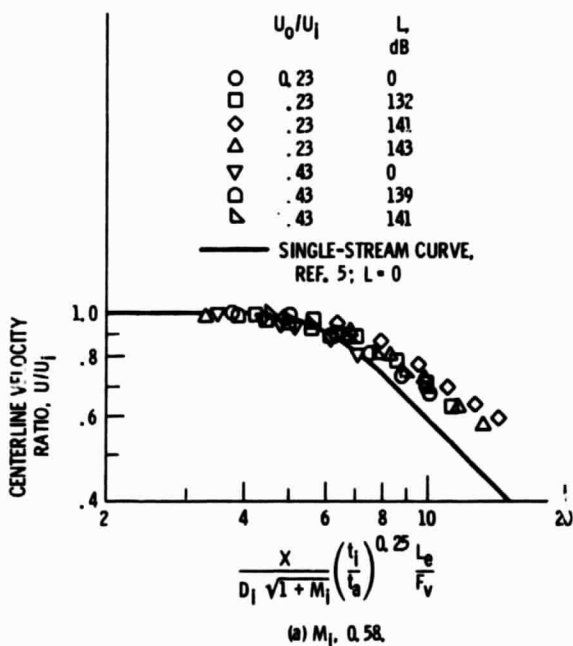
Figure 8. - Two-stream centerline velocity decay correlation including excitation and velocity ratio parameters.
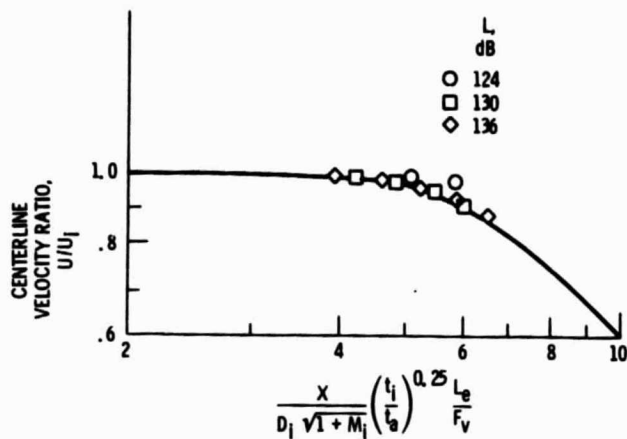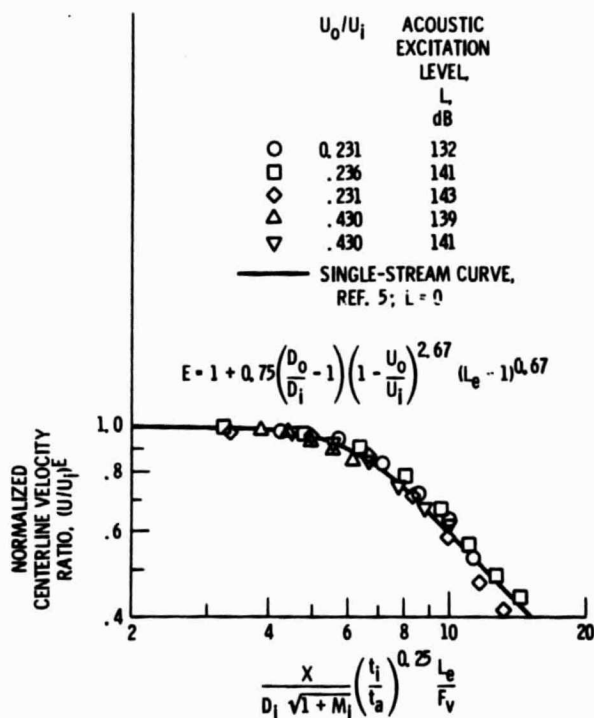
(b) M_i, 0.78; U_0/U_i, 0.22.

Figure 8. - Concluded.

$$E = 1 + 0.75\left(\frac{D_0}{D_i} - 1\right)\left(1 - \frac{U_0}{U_i}\right)^{2.67}(L_e - 1)^{0.67}$$

Figure 9. - Correlation of acoustically-excited two-stream centerline velocity decay using a normalized U/U_i (Ref. 4 data); M_i, 0.58.
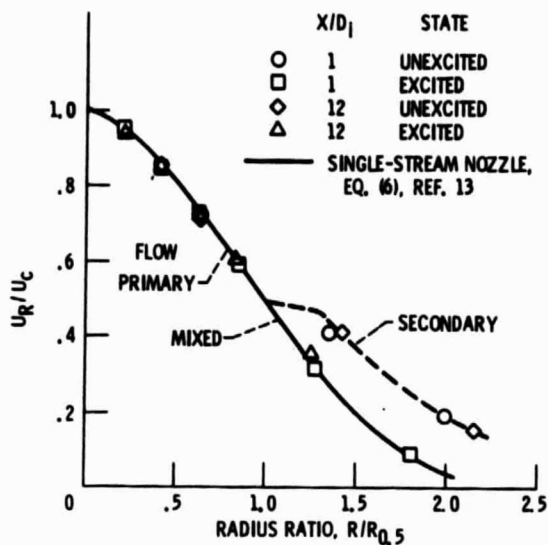
Figure 10. - Two-stream radial velocity profile with and without acoustic excitation. U_0/U_i, 0.5; internal excitation level, ~140 dB; (Ref. 10 data).
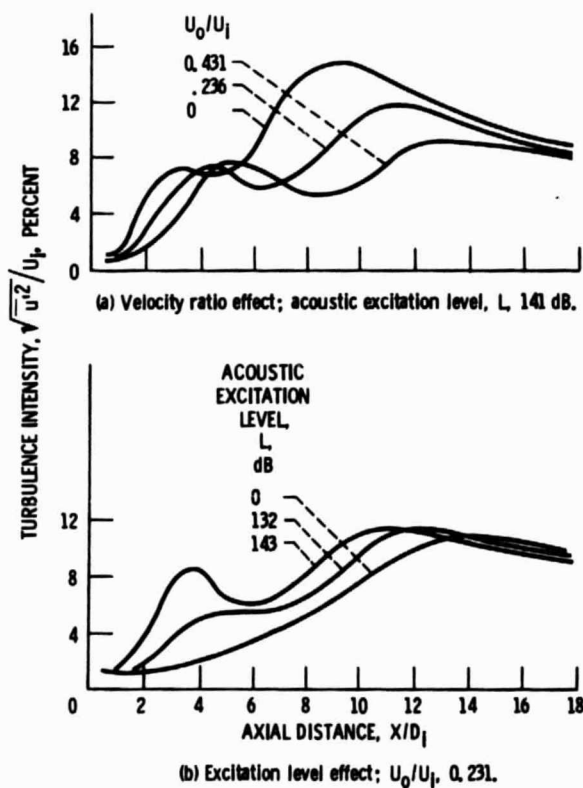

(a) Velocity ratio effect; acoustic excitation level, L, 141 dB.

(b) Excitation level effect; U_0/U_i, 0.231.

Figure 11. - Typical effects of acoustic excitation on two-stream centerline axial turbulence intensity (Ref. 4 data). M_i, 0.58; S, 0.5; (0, 0) mode.
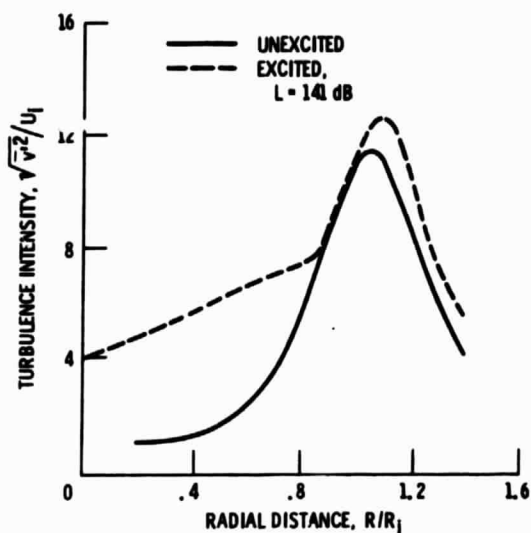
Figure 12. - Excitation effect on radial distribution of two-stream turbulence intensity at $X/D_j = 3$. M_j, 0.58; S, 0.5; (0,0) mode, (Ref. 4).
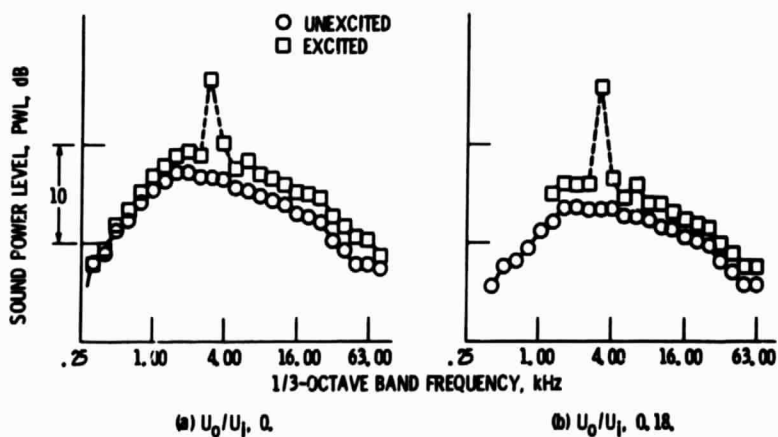

(a) U_o/U_j, 0.

(b) U_o/U_j, 0.18.

Figure 13. - Typical effect of acoustic excitation on sound power level with and without secondary flow. M_j, 0.78; (0,0) mode; excitation level, 136 dB; (Ref. 4).
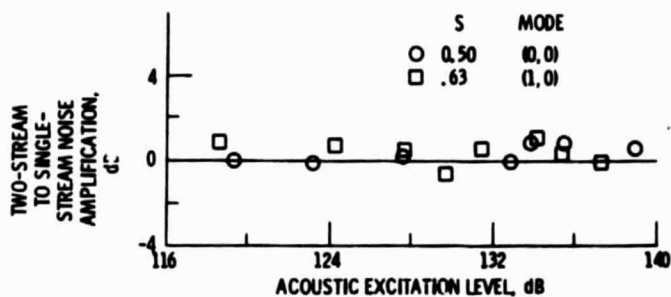
Figure 14. - Relative jet noise amplification for two-stream and single-stream jets at f = 5 kHz and θ = 90°. M_j, 0.78, U_o/U_j, 0.18; (Ref. 4).
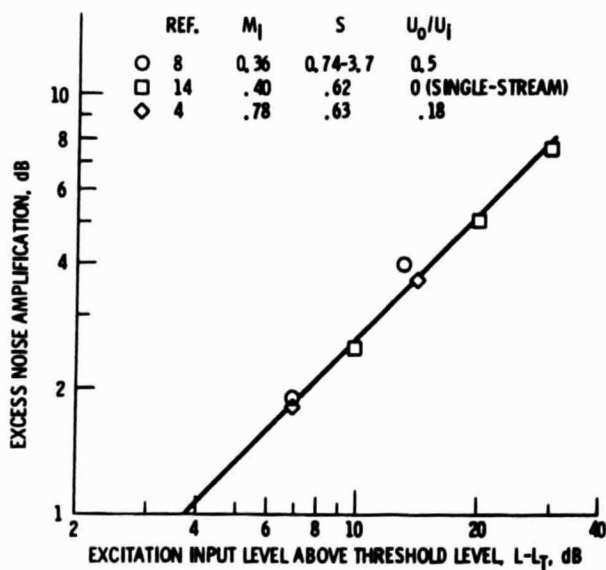

Figure 15. - Measured excess noise amplification as a function of acoustic input level.