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# Noise and Flow Structure of a Tone-Excited Jet

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**Detailed and well-controlled acoustic as well as turbulence measurements are made of a tone-excited jet to obtain an understanding of the mechanism of broadband noise augmentation. Results are presented for a range of excitation frequencies and levels both with and without flight simulation. Results of measurements of the large-scale instability waves within the excited jet are also described. Changes in the radiated noise and the flow structure and their interrelationship are then discussed.**

## Introduction

THE phenomenon of excitation of jets by sound has been known since the midnineteenth century.[1,2] It was not, however, until the relatively recent identification of the so-called large-scale coherent turbulence structure by Brown and Roshko[3] and Crow and Champagne[4] in 1971 that excited jets started receiving the attention of numerous other researchers.[5-15] It is now quite well established that forcing a jet by sound from upstream of a nozzle not only can increase the strength and regularity of the jet's coherent structures, but can also amplify the noise produced by the jet.[11-15]

The overall objective of the study described here was to obtain an understanding of the mechanism of the above-mentioned broadband jet noise amplification due to upstream excitation. This understanding was desired in terms of the relationship between the excitation characteristics, the changes in the large- and/or small-scale turbulence structure of the jet, and the sound radiated to the far field under both static and simulated forward velocity conditions.

The specific objective of this study was to answer the following two questions.

1) What is responsible for jet noise amplification: the large-scale turbulence structure or the small-scale turbulence?

2) Are the relative velocity effects the same for the excited and unexcited jets, when a forward velocity is imposed on the jet?

To achieve this objective, a four-part study was carried out: 1) a systematic set of acoustic measurements were made for a range of flow conditions in the acoustic research facility of the Lockheed Georgia Company; 2) turbulence measurements were made using Lockheed's laser velocimeter for those jet conditions at which jet noise amplification was found to be important; 3) to increase our understanding further, a few schlieren pictures of the excited jet were obtained; and 4) the theory to explain the results obtained in this investigation was developed. Only the experimental results are presented in this paper.

## Experimental Facility

The acoustic experiments were conducted in the anechoic open-jet facility located at the Lockheed-Georgia Research Center.[16] The facility is powered by a jet ejector and is capable of providing free-jet velocities of up to 92 m/s through a 71-cm exit diameter free-jet test section to simulate flight effects.

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The jet nozzle used in this study was a 5.08-cm-diameter convergent nozzle shown in Fig. 1a. As will be shown later, great pains were taken to provide 12 miniature probe tubes for acoustic mode detection at the nozzle-exit plane. The nozzle was connected to a 10-cm-diameter supply duct located at the center of the open-jet wind tunnel (Fig. 1b). As seen in Fig. 1b, the outer surface of the nozzle was made reasonably smooth by filling all of the slots and gaps needed to accommodate the miniature tubes and microphones with a high-temperature cement filler.

For efficient operation of Lockheed's facilities, turbulence measurements for this investigation were made in a facility

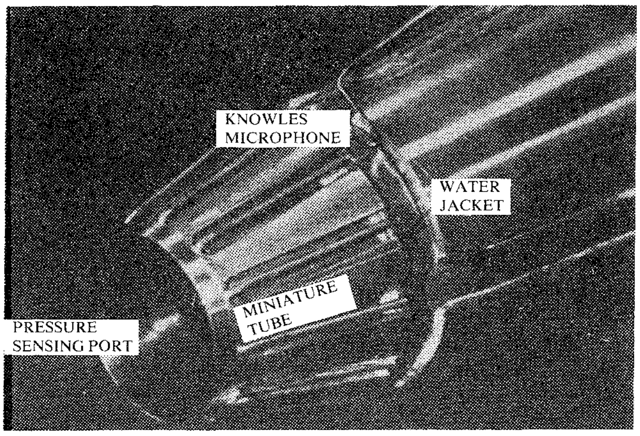



**Fig. 1a The test nozzle.**

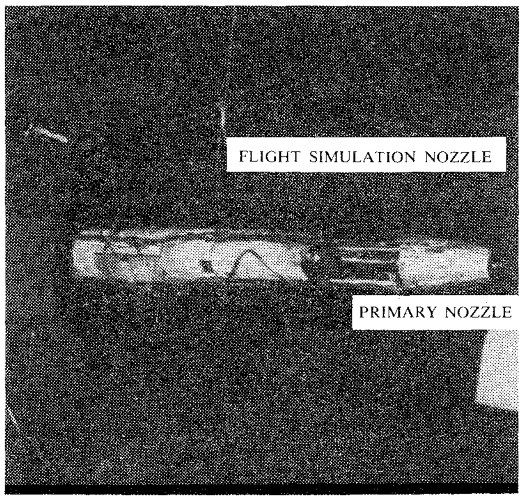



**Fig. 1b Test nozzle mounted in open-jet anechoic wind tunnel.**

that was similar to, but physically different from, that used for the acoustic measurements, and is shown schematically in Fig. 2. Unlike in the acoustic facility, in the turbulence facility the outer nozzle required to simulate flight effects was only 25 cm in diameter. To determine the extent of the model-jet flow that can be simulated adequately (for flight effects) by using a coannular nozzle system, extensive laser velocimeter measurements were made with different combinations of inner and outer nozzles to determine the boundaries of the inner and outer shear layers.[17] It was concluded from these results that, in the present setup, the primary jet can be simulated accurately for flight effects from the nozzle-exit plane to $X/D=12$.

The acoustic-source configuration is also shown in Fig. 2. It utilizes four electroacoustic 100-W Altec drivers. Each driver is enclosed in a pressure vessel to equalize the pressure across the driver diaphragm.

Since various constraints dictated the use of two separate facilities, it was important to carry out tests to ensure that the various flow and acoustic parameters of interest in both facilities did not differ significantly. Extensive validation tests were therefore carried out which showed that, for all intents and purposes, the two facilities produce the same results. It was found that, for both facilities, 1) turbulence intensity at the nozzle-exit center is about 0.6%, 2) the velocity profiles at the nozzle exit are identical, and 3) acoustic modes can be set up in isolation in each jet.

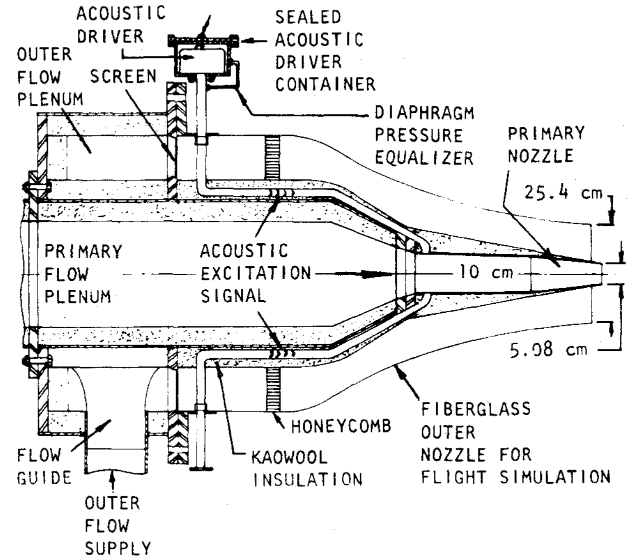



Fig. 2 Turbulence facility.

## Test Procedure and Data Acquisition

In the present study, both the plane-wave (0,0) and the first-order (1,0) spinning mode were generated in isolation by controlling the amplitudes and phases of the four acoustic drivers in the source section. To ensure that a given-order mode was obtained, both phases and amplitudes of sound at the nozzle-exit plane were measured by 12 miniature microphones, as shown in Fig. 1. A mode detection scheme proposed by Plumblee[18] was used in this study. Flow noise was rejected from the measured data by the use of cross-spectral analysis (for details see Ref. 17).

The mode detection scheme was used extensively in the acoustic facility. In the turbulence facility, however, because of the blockage of the sound-sensing ports by seeding particles, normally used in laser velocimetry, this method was not found to be sufficiently accurate. A survey of sound levels and phases at the nozzle-exit plane, with simultaneous iterative adjustments of the voltage and phase of the four acoustic drivers, was therefore made to set up and detect the desired modes.

Far-field acoustic measurements were made using 0.635-cm B&K microphones on a polar arc of radius 3.5 m at every 10 deg in the range 20 to 120 deg with the jet exhaust. The sound pressure levels (SPLs) were analyzed on a ⅓-octave band analyzer over the frequency range from 200 Hz to 80 kHz, and the results were recorded on an incremental digital tape recorder. The recorded levels were subsequently converted into lossless ⅓-octave SPLs by using a data reduction program that applies microphone frequency response corrections and atmospheric absorption corrections. The jet noise measured under flight simulation was corrected to ideal wind tunnel (IWT) conditions[16] and extrapolated to 100 equivalent diameters (5.08 m).

All mean velocity and turbulence measurements were made using Lockheed's forward-scatter, two-color, four-channel, laser velocimeter, used extensively in the past for jet-noise studies.[19] Both mean axial velocity and axial and radial components of turbulence intensity were measured.

The pressures associated with large-scale turbulence were measured using a 0.635-cm B&K microphone fitted with a nose cone and mounted on a faired microphone support. The levels were derived from the cross spectra between the electronic input to the acoustic driver and the microphone signal (see Ref. 17 for details).

## Test Conditions

Most of the data presented in this paper are for ambient temperature and for pressure ratios $\xi$ of 1.25 and 1.5. Limited data were acquired for a jet heated to a reservoir temperature $t_r=800$ K. Forward velocity effects were studied at tunnel velocities $V_t=45$ and 90 m/s.

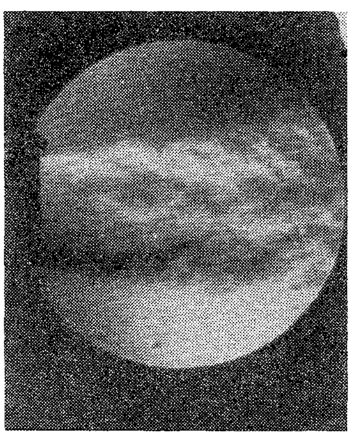
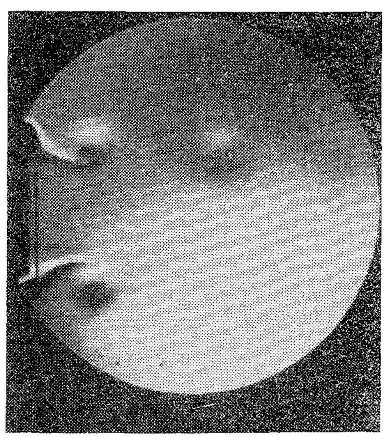
a)  b)  c) 

Fig. 3 Schlieren photographs of a) an unexcited and b) and c) an excited jet.

Besides the effects of flow conditions on jet noise and flow structure, the effects of excitation level and Strouhal number were also investigated for both the plane-wave mode and the first-order spinning mode. Optical measurements, described in the next section, were conducted to obtain qualitative results only and were obtained on a different jet rig[20] for a 21-m/s jet discharging from a 1.3-cm-diameter nozzle. Unless otherwise specified, all plotted results for the excited conditions are for the plane-wave mode.

## Optical Results

The so-called method of photographic averaging was used in the present experiments, but a new and very simple method of synchronizing the source of light was used.[20] The laser beam passing through a Bragg cell was the source of light. The Bragg cell shutter was synchronized with the excitation signal itself; thus the strobe frequency was the same frequency as that of the acoustic signal used to excite the jet.

Figures 3a and 3b show typical schlieren pictures of an unexcited and an excited jet. Here the light source was synchronized with the acoustic signal but the film plate was exposed only once. These pictures show quite clearly how the jet plume has widened considerably as a result of upstream excitation. Besides a general disruption occurring in the movement of the small-scale turbulence, new large-scale vortices appear to have formed some distance downstream, and where they appear in the schlieren photographs depends upon the phase relationship between this orderly vortex structure and the strobe signal.

To prove that these vortices are indeed orderly, the film plate was exposed 30 times using the aforementioned technique of photographic averaging. The resulting photograph is shown in Fig. 3c. The vortex structure seen here is the so-called large-scale structure, also called by some authors the "instability wave." Quantitative results associated with the large-scale structure will now be presented.

## Large-Scale Turbulence Pressure Amplitudes

As seen in Fig. 3, the large-scale turbulence structure in the excited jet is quite well defined. From measurements of the radially and axially fluctuating pressure within the flow, it was found that the frequency of the excited large-scale structure was the same as that of the acoustic excitation signal. An interesting feature was that the frequency bandwidth of this pressure fluctuation was extremely narrow ($\Delta f = 2$ Hz).[17]

Figure 4 shows a typical variation of the large-scale turbulence pressure magnitude with distance along the axis. Here the jet was excited with a discrete tone at Strouhal number $S_e = f_e D/U = 0.5$. The topmost curve was obtained at an excitation level of 141 dB. The same figure shows the pressure variation with the flow turned off, but with the excitation level kept at 141 dB. It is clear from this figure that, in the presence of the jet flow, the acoustic signal is dominant close to the nozzle exit up to about ½-diameter. Thereafter the hydrodynamic-wave magnitude starts rising very rapidly, reaches a peak, and is then followed by a gradual decrease in level. The fluctuating pressure due to the large-scale structure is about 35 dB higher than that due to the acoustic signal.

Curves of the large-scale instability wave are not necessarily parallel to each other for various excitation levels, as seen in Fig. 4 for three different excitation levels, i.e., 141, 136, and 128 dB. Close to the nozzle exit the behavior is linear, but further downstream there is considerably less amplification at the higher excitation levels. At large distances downstream, in fact, there is even a decrease in the measured turbulence level for an increase in excitation level.

These results can be explained as follows.[17,21] When the jet is excited by a low-level acoustic source, the large-scale instability wave tends to lock onto it, and produces a response

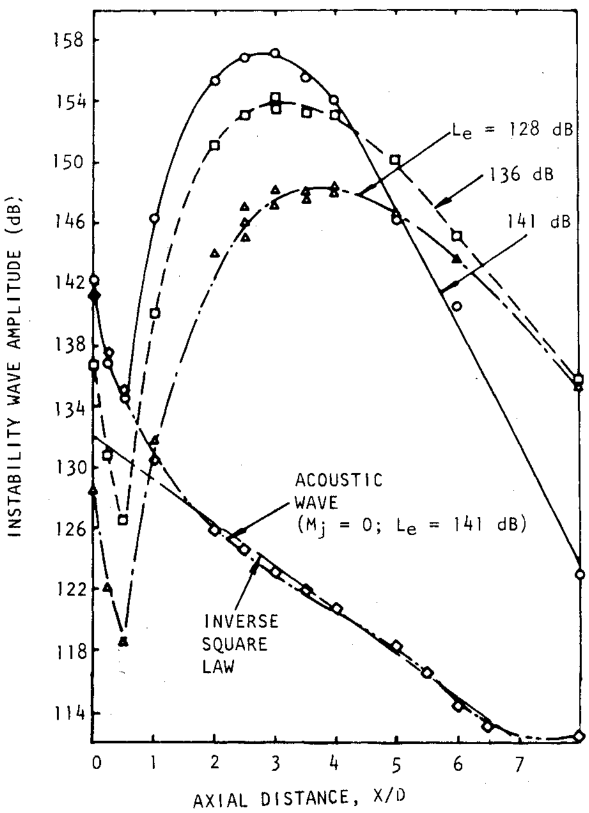



Fig. 4 Centerline variation of instability-wave amplitude at various excitation levels ($M_j = 0.58$; $U_j = 195$ m/s; $S_e = 0.5$).

that is in agreement with linear shear-layer instability theory. The instability wave extracts energy from the mean flow in the initial region of the jet, as indicated by the initial rise of the curve in Fig. 4. However, further downstream, because of larger jet width, the growth rate of the instability wave is decreased, and as the wave decays, part of its energy is transferred back to the mean flow. Thus, at low excitation levels, there is basically a back and forth exchange of energy between the instability wave and mean flow. At higher excitation levels, however, the wave extracts considerable energy from the jet mean flow, and the response becomes nonlinear as some of this energy is converted into turbulent energy. This interaction involves both the generation and transport of random turbulence.

The increase in the level of the random turbulent kinetic energy causes a more rapid spreading of the jet flow through an increase in turbulent stresses. Thus, for high-level excitation, some distance downstream of the nozzle exit (e.g., beyond the peak of the upper curve in Fig. 4), the wave transfers more energy to the random turbulence than it gains from the mean flow, and it begins to decay rapidly. Based upon these and other results, not presented here but described in Ref. 17, the effect of nonlinearity is to lower the peak of the amplification curve and move it back toward the nozzle. The severity of this effect depends upon the strength and frequency of the excitation and the mean velocity of the jet flow. Similar results were observed by Moore.[12]

## Turbulence Results

Because of the time-consuming nature of turbulence-data acquisition, the flow and excitation parameters for which the turbulence data were acquired were dictated by those conditions that provided maximum jet noise amplification. As shown in the next section on acoustic results, maximum amplification was obtained when the jet was excited at a Strouhal number of 0.5. Most of the turbulence data were therefore acquired at this Strouhal number. Even though data

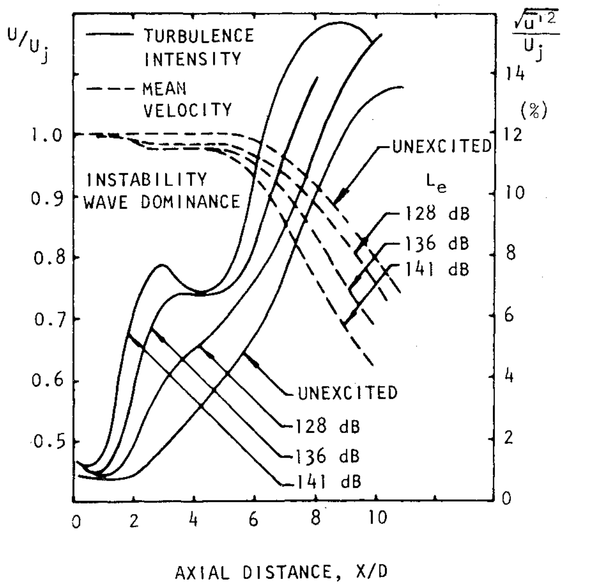



**Fig. 5 Excitation level effects on centerline distributions ($M_j = 0.58$; $U_j = 195$ m/s; static; $S_e = 0.5$).**

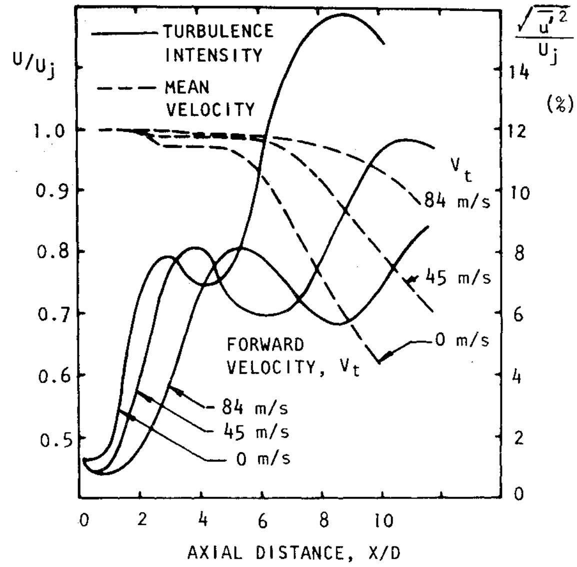



**Fig. 7 Flight effects on excited jets: centerline distributions ($M_j = 0.58$; $U_j = 195$ m/s; $S_e = 0.5$; $L_e = 141$ dB).**

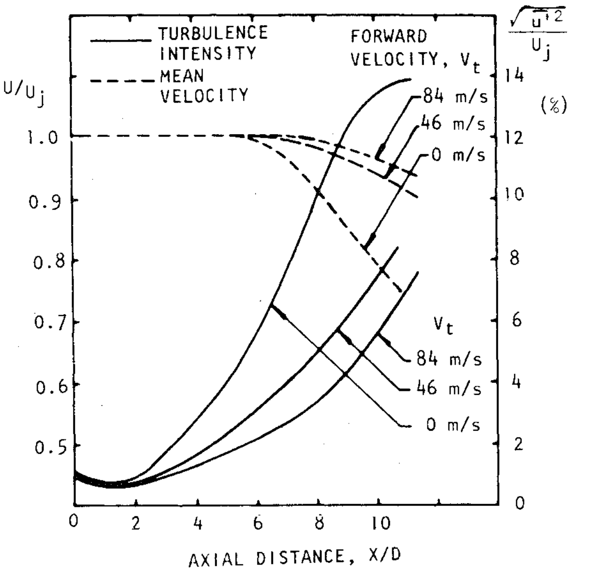



**Fig. 6 Flight effects on unexcited jets: centerline distributions ($M_j = 0.58$; $U_j = 195$ m/s).**

for two jet Mach numbers ($M_j = 0.58$ and 0.79) and two temperatures were acquired, only a limited amount of data, mostly for $M_j = 0.58$ and unheated conditions, will be presented.

To preserve clarity of the plotted turbulence results, it was decided to show smooth curves through the measured points instead of all the individually measured points. The maximum deviation of the measured points from the best-fitting curve was $\pm 0.04$ for the dimensionless mean velocity and $\pm 1.0\%$ for the turbulence intensity throughout the whole range of the experimental conditions.

#### Excitation Level Effects

The effects of excitation level on centerline distribution of mean velocity and turbulence intensities are shown in Fig. 5. Mean-velocity data clearly show that, as the excitation level is increased, the potential core is reduced in length. This effect is further seen in the plots of centerline distribution of turbulence intensities, where it is found that the turbulence intensities increase as a result of increased upstream excitation level. It is to be noted that, at higher levels of excitation, the turbulence intensity distribution has a hump between 2 and 3 diameters downstream. This is because these plots are for the total fluctuating velocity intensity, which includes components from the small-scale as well as the large-scale turbulence. Beyond about 5 to 6 diameters, however, the contribution from the large-scale turbulence is minimal and most of the changes in turbulence intensity are due to the small-scale turbulence. Similar results were obtained for other Mach numbers.[17]

#### Forward Velocity Effects

To show the effects of forward velocity on jet noise amplification, it is best first to present data for unexcited jets. Figure 6 shows the effects of forward velocity on both the mean velocity and the turbulence intensities. Clearly, as the forward velocity is increased, the potential-core length increases and the turbulence intensities decrease. These effects are quite drastic; for example, the turbulence intensity at $X/D = 8$, due to the forward velocity of 34 m/s, has decreased from about 10 to 3.5%.

When the jet is excited and a forward velocity is superimposed, the results appear to be very similar to those for the static case. Typical results are presented in Fig. 7. As for the static case (Fig. 5), the potential core is reduced as a result of excitation. Similarly, the turbulence intensities are reduced at all axial stations up to 10 exit diameters.

It is to be noted that, in the centerline distribution of turbulence intensities shown in Fig. 7, the magnitude of the first hump for each forward velocity condition has not changed significantly. Since, as mentioned earlier, this hump is dominated by the turbulence intensity associated with the large-scale turbulence, it is reasonable to assume that the large-scale structure growth rate in this case has not changed significantly even in the presence of a coflowing stream. The theoretically derived coupling constants[17] between the excitation signal and the large-scale turbulence structure for this experimental arrangement also do not alter significantly with forward velocity. This is especially true for the low range of secondary-to-primary velocities used in the experiment.

The preceding arguments are best substantiated by comparing the shear-layer thicknesses of the unexcited and excited conditions both with and without forward velocity. This comparison is shown in Fig. 8, where the half-velocity shear-layer thickness $b$ (defined in the figure) is plotted against axial

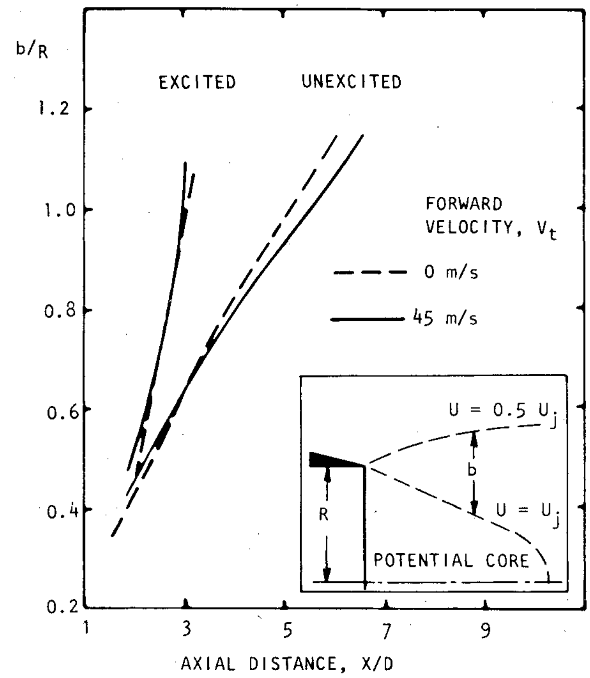



**Fig. 8 Effect of excitation on half-velocity shear-layer widths ($M_j$ = 0.58; $U_j$ = 195 m/s; $L_e$ = 141 dB; $S_e$ = 0.5).**

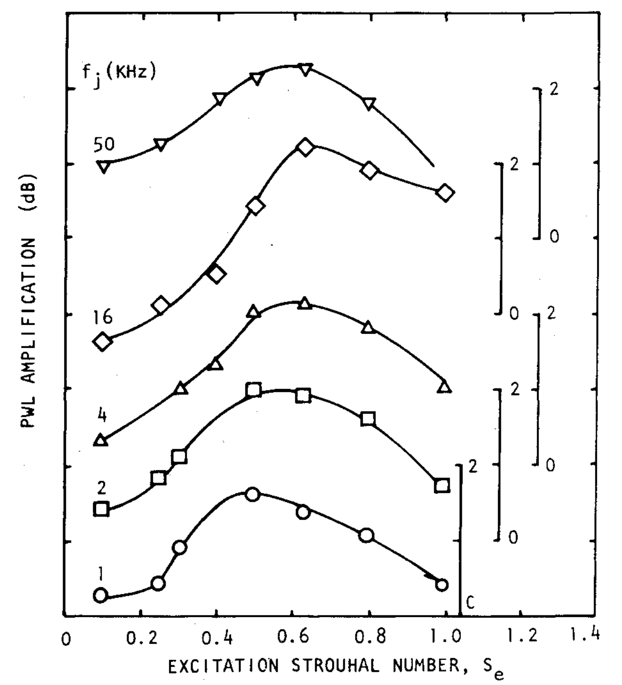



**Fig. 9 Variation of jet-noise power amplification with excitation Strouhal number at various jet-noise frequencies ($M_j$ = 0.79, $U_j$ = 251 m/s; $L_e$ = 136 dB).**

distance. Clearly there is little change in plume width whether or not the forward velocity is included.

### Mach Number Effects

It was found that the higher the jet Mach number, the lower the level of turbulence intensity. This appeared to apply to both large-scale (near $X/D = 2$) and small-scale turbulence intensities. It will be shown later that these results bear a direct relationship to the jet-noise-amplification dependence on jet Mach numbers.

## Acoustic Results

### Strouhal Number Effects

For a given excitation level, the maximum jet noise amplification was found to lie between $S_e = 0.5$ and 1.0, depending upon whether the amplification at a given frequency was considered or whether the overall acoustic sound pressure level (OASPL) data, after subjective subtraction of the contribution of excitation from the discrete tone, were examined. The outcome was somewhat different if the amplification in the far-field acoustic power was considered.

Published literature is inconsistent with respect to the effect of excitation Strouhal number on far-field acoustic radiation. For example, Moore[12] considered only the OASPLs at a selected angle, whereas Jubelin[14] considered overall acoustic powers. In the present investigation, in addition to SPL spectra and OASPLs, the ⅓-octave acoustic power spectra and overall power levels (OAPWLs) are also calculated. The OASPLs and OAPWLs are calculated by removing the discrete tones from the corresponding spectral plots. As reported in Refs. 11, 12 and 14, it was found that exciting the jet by discrete tone sound amplified jet mixing noise at all frequencies at certain excitation Strouhal numbers and above certain excitation levels.

Typical results showing the amplification in the ⅓-octave PWLs at various positions in the jet noise spectrum are shown in Fig. 9 as a function of excitation Strouhal number. These results show that the peak of the amplification curve is a function of the jet noise frequency, which basically lies between $S_e = 0.5$ and 0.63.

In general, the peak amplification in tone-corrected OASPLs is also found to occur between $S_e = 0.5$ and 0.63.

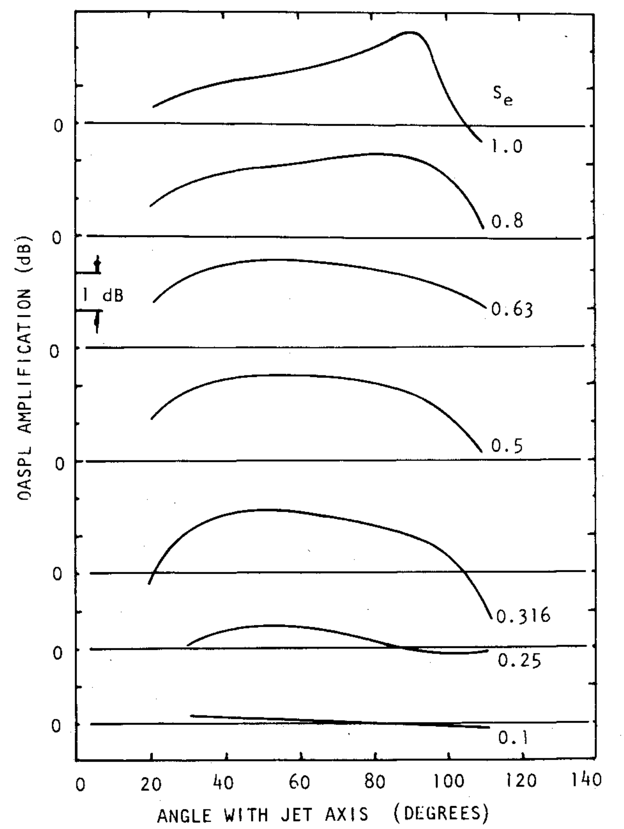



**Fig. 10 Variation of jet noise OASPL-amplification directivity with excitation Strouhal number $S_e$ ($M_j$ = 0.79; $U_j$ = 251 m/s; $L_e$ = 136 dB).**

This amplification is noted at almost all measurement angles. Typical results are shown in Fig. 10. Most amplification is, however, obtained at angles between 40 and 90 deg to the downstream jet axis. Outside this range of angles, the amplifications reduce sharply; in fact, for lower Strouhal numbers, an attenuation in jet noise is observed, particularly in the forward arc.

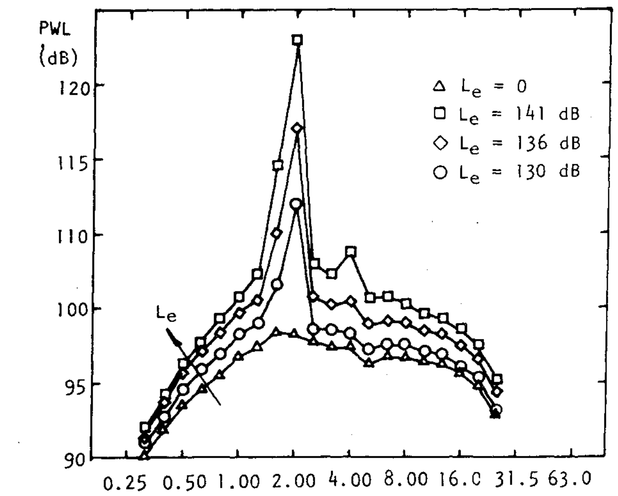



**Fig. 11 Effect of excitation level $L_e$ on far-field acoustic power ($M_j = 0.58$; $U_j = 190$ m/s).**

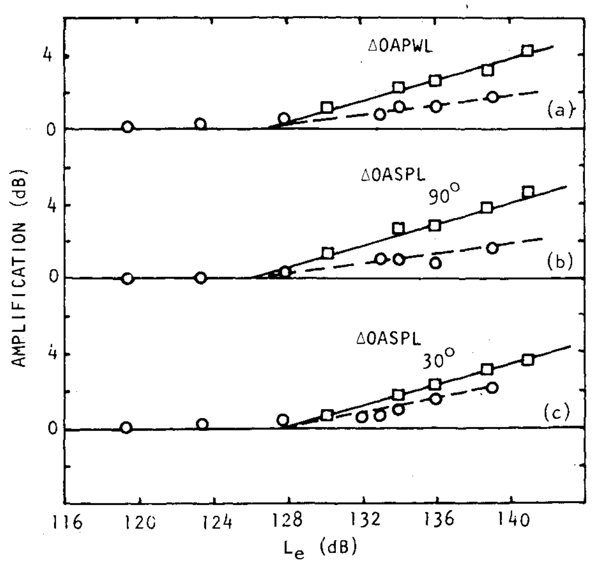



**Fig. 12 Variation of OAPWLs and OASPLs with excitation level and Mach number (□, $M_j = 0.5$; ○, $M_j = 0.79$; $S_e = 0.5$).**

Based upon these and other results presented by the authors in Ref. 17, it was decided to consider $S_e = 0.5$ as a typical *peak* Strouhal number to assess the effects of other excitation parameters on jet noise amplification.

#### Excitation Level Effects

Effects of increasing the magnitude of the upstream excitation tone are shown in Fig. 11. Far-field acoustic power spectra are compared for four different excitation levels, namely, unexcited, 130, 136, and 141 dB. Clearly, as the excitation level is increased, further amplification is obtained at all frequencies. This effect is further illustrated in Fig. 12, where the tone-corrected amplifications in OAPWLs and also OASPLs at polar angles of 30 and 90 deg to the downstream jet axis are presented for two jet Mach numbers ($M_j = 0.57$ and 0.79) as a function of excitation level $L_e$. Clearly there appears to be a threshold below which there is no amplification, but above which the amplification increases linearly with excitation.

The results shown in Fig. 12 also indicate that, for a given excitation level, the higher the jet Mach number, the lower the jet noise amplification. This is consistent with the turbulence results where it was found that, as a result of upstream excitation, the turbulence intensities increased much more for lower Mach numbers at a given excitation level.

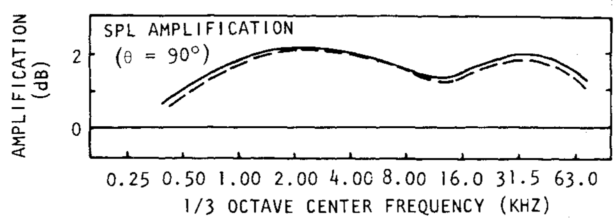



**Fig. 13 Effect of forward velocity $V_t$ on jet noise amplification ($M_j = 0.79$; $U_j = 190$ m/s; $S_e = 0.5$; $L_e = 134$ dB).**

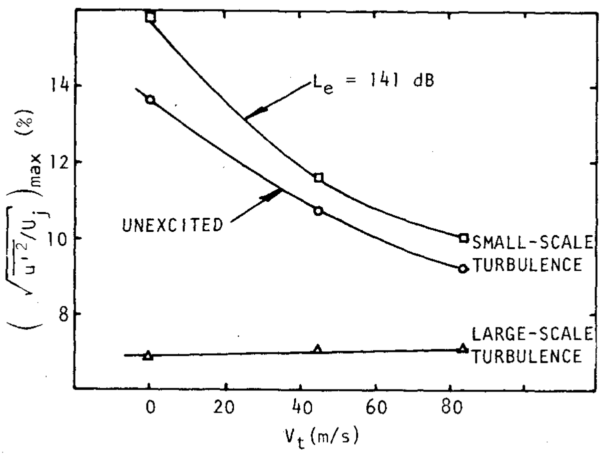



**Fig. 14 Variation of peak centerline turbulence intensities with forward velocity $V_t$ ($M_j = 0.58$; $U_j = 195$ m/s; $S_e = 0.5$).**

#### Forward Velocity Effects

The jet noise amplification for both the static and flight simulation conditions was found to be within a decibel or so. Typical amplification spectra for ⅓-octave SPLs at 90 deg for forward velocity $V_t = 0$ and 45 m/s are compared in Fig. 13. It should be noted that in the curves shown here the tones due to excitation have been smoothed out.

These acoustic results are difficult to relate to the turbulence results quantitatively, but they resemble one another qualitatively in that the changes due to excitation in the flow parameters followed similar trends with and without flight simulation.

#### Temperature Effects

In most of the data acquired for the heated case, little jet noise amplification was observed. Limited data from turbulence measurements also indicated little change in turbulence for heated and excited jets. These results are in contradiction with the acoustic results presented by Jubelin.[14] Because of the limited range of flow and excitation conditions for the heated-jet data in the present study, it is dangerous to draw firm conclusions about jet noise amplification for heated jets. Further research is clearly needed to study heated, excited jets.

## Conclusions

A fairly detailed study to understand the phenomenon of jet noise amplification has been carried out. This was done by acquiring simultaneous acoustic, mean velocity, turbulence, and instability-wave pressure data with and without forward velocity effects. Some optical data were also acquired to improve understanding further. Limited data for heated jets were also obtained.

Although not presented here, a theoretical model was developed as part of this study to explain the jet noise amplification.[17] After all the experimental results and the theoretical model are put together, jet noise amplification can be fairly well described by a *three*-part process.

The crux of the problem and *first* part of the process appears to be the large-scale turbulence structures. It is now well known that these large-scale structures are an inherent part of a fully developed turbulent free-shear flow. When a shear layer is excited by discrete tone sound waves of appropriate frequency, not only is the randomness of the large-scale turbulence structure drastically reduced, but also its amplitude is greatly enhanced.

The *second* part of the process involves the coupling between the large-scale structure and the fine-scale turbulence based on the premise that, even in the unexcited jet, these two are intimately related. Thus, if the large-scale structure controls the mixing process (with ambient air) and hence the mean- and turbulent flow properties in an unexcited jet, then the augmented large-scale structure in an excited jet can be expected to produce significant changes in the fine-scale turbulence values, as was indeed seen in this study.

The *final* link in the process concerns the relationship between the jet flow characteristics and the noise radiated to the far field. Here, on the basis of classical aerodynamic noise theories, it is straightforward and logical to infer that an excited jet with significantly modified mean flow and turbulence levels will generate different noise levels compared with an unexcited jet.

The changes in large-scale and small-scale jet flow properties brought about by upstream excitation are acknowledged widely by jet noise researchers, but when it comes to the changes in noise fields between unexcited and excited jets, two schools of thought have clearly emerged recently. In one case, it is argued that the increase in jet noise is a direct result of the amplified large-scale turbulence, whereas the small-scale turbulence plays a relatively weaker role in noise generation. This is the explanation put forward in a recent theoretical study by Ffowcs Williams and Kempton.[13] On the other hand, the position taken by other researchers places more importance on the increase in small-scale turbulence in an excited jet. Here it is argued that, although the phase-locked large-scale turbulence structure is at the root of noise amplification, the actual noise-generation mechanism lies in the small-scale turbulence.[21,22]

The present results support the second explanation. The broadband jet noise observed in these experiments and in those of others[11,12,14] is almost uniform at all frequencies. If the large-scale structure were directly responsible for noise amplification, the noise increase would occur only over a narrow frequency band, centered around the natural frequency of the instability wave, which would also correspond to the frequency of excitation. In addition, except for heated jets or unheated jets with relatively high supersonic jet Mach numbers ($M_j > 1.5$), the phase velocity of the excited large-scale instability waves is subsonic relative to the ambient fluid. It can be shown theoretically[22] that such subsonic instability waves are very inefficient in generating sound waves directly.

The preceding statements are further confirmed if the peak turbulence intensities associated with the large-scale structure and the small-scale structure are plotted against forward velocity, as shown in Fig. 14, and examined. It is seen that, for a given upstream excitation level of 141 dB, the change in the large-scale turbulence is negligible with forward velocity, but the small-scale turbulence decreases with increasing forward velocity for the unexcited as well as the excited jet. As expected, the small-scale turbulence levels are higher for the excited jet and the effect of forward velocity is similar to that for the unexcited jet. It is noted that the difference between the turbulence intensity levels for the excited and unexcited conditions does not alter significantly with forward velocity. Also, since the corresponding difference in far-field noise also did not change significantly, it is a further indication of the fact that, ultimately, it is the changes in small-scale turbulence that are responsible for jet noise amplification.

## Acknowledgments

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