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Acoustic Excitation—A Promising New Means of Controlling Shear Layers

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ACOUSTIC EXCITATION - A PROMISING NEW MEANS OF CONTROLLING SHEAR LAYERS

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SUMMARY

Techniques have long been sought for the controlled modification of turbulent shear layers, such as in jets, wakes, boundary layers, and separated flows. Relatively recently published results of laboratory experiments have established that coherent structures exist within turbulent flows. These results indicate that even apparently chaotic flow fields can contain deterministic, nonrandom elements. Even more recently published results show that deliberate acoustic excitation of these coherent structures has a significant effect on the mixing characteristics of shear layers. Therefore, we have initiated a research effort to develop both an understanding of the interaction mechanisms and the ability to use it to favorably modify various shear layers. Acoustic excitation circumvents the need for pumping significant flow rates, as required by suction or blowing. Control of flows by intentional excitation of natural flow instabilities involves new and largely unexplored phenomena and offers considerable potential for improving component performance. Nonintrusive techniques for flow field control may permit much more efficient, flexible propulsion systems and aircraft designs, including means of stall avoidance and recovery. The techniques developed may also find application in many other areas where mixing is important, such as reactors, continuous lasers, rocket engines, and fluidic devices. It is the objective of this paper to examine some potential applications of the acoustic excitation technique to various shear layer flows of practical aerospace systems.

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INTRODUCTION

Techniques have long been sought for the controlled modification of various flow fields, such as jets, wakes, boundary layers, and separated flows. Relatively recently published results of laboratory experiments have established that coherent structures exist even within turbulent flows. These results indicate that even these apparently chaotic flow fields contain deterministic, nonrandom elements (e.g., refs. 1 to 8). Even more recently published results show that deliberate aeroacoustic excitation of these coherent structures has a significant effect on the mixing characteristics of shear layers. Control of flows by intentional excitation of natural flow instabilities involves new and largely unexplored phenomena and offers considerable potential for improving component performance. Nonintrusive techniques for flow-field control may permit much more efficient, flexible propulsion systems and aircraft designs, including means of stall avoidance and recovery. The techniques developed may also find application in many other areas where mixing is important, such as reactors, continuous lasers, rocket engines, and fluidic devices.

Therefore, the NASA Lewis Research Center has initiated a research effort to develop an understanding of the interaction mechanisms and to develop the technology to favorably modify various shear layers without resorting to "brute force" methods such as suction and blowing. Acoustic excitation circumvents the need for pumping significant flow rates, as required by suction or blowing. Since there are many gaps in our fundamental understanding of the unsteady aerodynamic processes involved, broad fundamental experimental, theoretical, and numerical studies are needed and some have been initiated. We have also begun preliminary studies to identify those applications exhibiting the greatest potential payoff, as will be described in this paper.

It has been recognized for some time that the structure of shear layers is sensitive to excitation by acoustic waves (e.g., refs. 9 to 24). The mechanism of this excitation was considered by Ahuja, et al. (ref. 25) to be approximated by a three-step process, as illustrated in figure 1. In the first step, instability waves, inherent in even an unexcited shear layer can be modified by disturbances, such as acoustic tones, leading to an amplification of the instability wave (e.g., refs. 26 and 27). The magnitude of this modification is dependent on the detailed characteristics of the flow field and the excitation signal. The second step of the process involves the coupling between the coherent structure and the random, or fine-scale, turbulence. These changes then combine to affect other processes such as the gross mixing rate and noise generation. In reality the excitation process may be even more complicated, and nonlinear effects may be important (e.g., refs. 28 and 29).

Striking evidence of jet mixing enhancement by this process has been shown by Ahuja, et al. (ref. 25) for a circular jet exhausting into a quiescent atmosphere. Schlieren photographs obtained with laser lighting are shown in figures 2 and 3. The unexcited jet is shown in figure 2(a). In figure 2(b) the jet is excited by an upstream acoustic signal at excitation Strouhal number, $S_e = f_e D_j / V_j = 0.5$, where f_e is the excitation frequency, D_j is the jet diameter, and V_j is the jet velocity. (All symbols are defined in the appendix.) Further insight into the excitation process is shown in figure 3. In these cases, the laser light source is strobed at the excitation frequency; this accentuates those phenomena occurring at the excitation frequency (or its higher harmonics) and washes out those phenomena occurring at any other frequencies. In figure 3(a) the excitation frequency corresponds to a Strouhal number, $S_e = 0.5$. Due to this photographic enhancement process, the large-scale coherent structure can clearly be seen. When the excitation frequency is doubled, $S_e = 1.0$ (fig. 3(b)), the size of the coherent structure is reduced and the spacing between successive structures is halved. These results indicate the sensitivity of the excitation process to the frequency of the imposed disturbance.

More recently it has been shown by Ahuja, et al. (ref. 30) that acoustic excitation can also influence the flow over an airfoil. These results are shown photographically with smoke flow visualization in figure 4. The airflow is from right to left over an airfoil at a 26° angle of attack. The boundary layer is tripped near the leading edge to produce a turbulent boundary layer. At this high angle of attack the flow is separated in the unexcited case (fig. 4(a)). The effect of excitation is illustrated in figure 4(b) for a Strouhal number, $S_e = f_e C / V_0 \cong 4$, where C is the wing chord and V_0 is the free-stream velocity. With excitation the flow remains nearly attached over much more of the airfoil, and the lift coefficient is significantly increased. It was also shown in reference 30 that drag reduction can be obtained with higher frequency excitation, $S_e \cong 20$.

POTENTIAL APPLICATIONS

Considering the phenomena described in the INTRODUCTION a wide range of specific applications can be envisioned. It is useful to identify four general types of applications:

(1) low-frequency excitation of free shear layers,

(2) high-frequency excitation of free shear layers,

(3) low-frequency excitation of boundary layers, and

(4) high-frequency excitation of boundary layers.

The low-frequency applications involve augmented mixing achieved by exciting the naturally dominant structures. The high frequency applications involve suppressed mixing achieved by exciting structures of a smaller scale than that of the naturally dominant structures, thereby preventing these larger structures from dominating (and enhancing) the mixing process. A review of the literature pertinent to these applications is presented by Lepicovsky, et al. (ref. 31).

In figure 5, specific areas of applications are listed for each of the four general types of application. The following subsections briefly describe these specific areas of potential application. Preliminary assessments of several of the more promising possibilities are presented later in the paper.

Externally Blown Flap

Under-the-wing (UTW) and over-the-wing (OTW) externally blown flap systems are used to provide high lift for short takeoff and landing (STOL) aircraft. The rapid axial velocity decay and jet spreading produced by enhanced mixing (e.g., refs. 25 and 31 to 40), as illustrated in figure 6, can be extremely useful in reducing jet/flap interaction noise and the aerodynamic and thermal loads on the flaps. (Although illustrated here for the UTW case, excitation would also be applicable to OTW systems). The noise of such aircraft not only has an environmental impact, but also contributes to structural fatigue because of its strong, very low frequency content. The control of flow separation at high flap angles by excitation, as described in a later section may also be useful.

The externally blown flap (EBF) concept is one of the simpler approaches to achieving powered lift for turbofan-powered short-takeoff-and-landing (STOL) aircraft (e.g., ref. 41). Unfortunately, a considerable amount of noise and acoustically-related flap loading is produced by the interaction of the engine exhaust with the surfaces of the flap system (e.g., ref. 42). In fact, with under-the-wing (UTW) EBF systems the flap interaction noise is the dominant aircraft noise source when highly-noise-suppressed turbofan engines are employed (ref. 42). Therefore, NASA conducted an extensive research program to determine the flap noise for a variety of EBF configurations to provide insight into flap noise source mechanisms (refs. 42 to 50). These efforts were accompanied by special tests and programs aimed at suppressing flap noise (refs. 51 to 56).

Initially most of the research and development effort was directed towards the UTW system because such an aircraft could more readily be evolved from current conventional commercial (CTOL) aircraft. However as the magnitude of the flap noise problem became more clearly understood, there was increased emphasis on determining the acoustic characteristics of OTW EBF systems (refs. 44, 49, and 50). The OTW system takes advantage of the high frequency acoustic shielding provided by the wing and flap system and therefore offers the promise of reducing the flap noise perceived below an aircraft.

Among the many flap noise source mechanisms thought to contribute to the UTW noise field are: (1) flap leading edge noise caused by incident turbulence in the exhaust jet; (2) scrubbing noise generated by turbulence produced in the jet-mixing region and convected along the surfaces of the wing and flaps; (3) noise from separated flow on the flaps; (4) trailing-edge noise caused by turbulent eddies and/or shed vortices as they pass the trailing edge of the flap; and (5) jet mixing noise originating in the distorted and deflected exhaust jet.

With the OTW configuration the noise sources (ref. 44) appear to be similar to the UTW sources with several important differences. First, there is no flap leading edge noise source, as the flap slots are normally covered. In some cases, exhaust flow deflectors may be used to facilitate flow attachment to the wing-flap system (e.g., ref. 49). The presence of a flow deflector introduces an additional broadband source of noise (similar to UTW flap noise) above the wing.

Generally the impingement noise is dominant in the forward quadrant below the wing of a blown flap system, and because of its high intensity, usually dominates the peak flyover noise. In this region it will be assumed (see refs. 46 and 57) that the mean-square acoustic pressure, $\overline{p^2}$, for the low frequency portion of the flap noise spectrum can be represented (ref. 41) by

$$\overline{p^2} \sim \left(\frac{\rho_a}{Rc_a}\right)^2 \int_A I_i^2 V_i^6 \, dA \tag{1}$$

where the integral is based on the radial profile of the jet impingement velocity, V_i, and the inflow turbulence intensity, I_i, at the flap axial station. (All symbols are defined in the appendix.) The integral form of equation (1) results from taking into account the strong velocity and turbulence gradients present in the jet exhaust plume (in contrast to an airfoil immersed in a uniform flow field). Inasmuch as flap noise spectra peak at low frequency, the overall sound pressure level (OASPL) can be represented by equation (1) with good accuracy. It was assumed in deriving equation (1) that the flap noise is independent of the exhaust plume temperature. The effect of temperature has not been established at this time but is thought to be small in the velocity range of interest. This assumption allows the density term to be taken outside the integral in equation (1).

For EBF systems having similar radial turbulence intensity profiles and similar impingement velocity profiles at the flap impingement station, the integral of equation (1) can be approximated for scaling purposes by the technique used in references 45 and 46 to give the simplified relation (ref. 41),

$$\overline{p^2} \sim \left(\frac{\rho_a}{Rc_a}\right)^2 \; A_i V_{i,p}^6 \tag{2}$$

where $A_i = (\pi/4)D_i^2$ and $V_{i,p}$ is the peak impingement velocity (ref. 53) obtained from the nozzle velocity profile at the flap station. The characteristic impingement diameter, D_i, is arbitrarily taken, for scaling purposes, as the width of the profile at the flap station where the velocity is 80 percent of the peak impingement velocity. Both $V_{i,p}$ and D_i are obtained from nozzle exhaust velocity radial profiles measured without the presence of the wing and flap system. Examining this relationship (eq. (2)) indicates the means by which excitation can reduce flap noise and the related loads.

As shown by Ahuja, et al. (ref. 25) the jet centerline velocity, which would correspond to the peak impingement velocity, $V_{i,p}$, can be substantially reduced by excitation (as shown in fig. 7). Although the rate of jet spreading is increased, the effect on impingement area based on the $V_i/V_{i,p} = 0.8$ contour would be minimal (as shown in fig. 8). At a typical nozzle-to-flap spacing, $X/D_i = 7$, the data of figure 12 indicate that for the highest excitation level, $V_{i,p}$ would be reduced to 0.88 of its unexcited value; the resulting impingement noise would be reduced about 3.5 dB. This reduction would have to be qualified by the increase in mixing noise which accompanies the enhanced mixing, but this mixing noise is typically 10 to [illegible] dB below the impingement noise (e.g., ref. 43).

Correlations developed by von Glahn from model scale data on the effect of excitation on unheated jet mixing (refs. 32 and 33) could be used along with equation (2) to predict noise reduction benefits over a wide range of conditions. The effect of acoustic excitation on centerline velocity decay has been found by Ahuja, et al. (ref. 25) to be essentially the same under simulated flight conditions, as shown by the experimental data in figure 9. These flight effects are included in von Glahn's correlation (ref. 32) as is also shown in figure 9. However, scaling to larger sizes has not yet been demonstrated, and little information exists on temperature effects. These technology needs will subsequently be discussed further.

Perhaps the greatest benefits of excitation would be minimizing the installation penalties associated with suppressing noise to a given level. Because of the importance of reducing jet/flap interaction noise and flap loads, external-mixer decayer nozzles have been used, for example on the YC-15 STOL airplane as shown in figure 10 (ref. 58). Such nozzles were also evaluated in the NASA Quiet, Clean, Short-Haul Experimental Engine (QCSEE) Program to determine their economical attractiveness for the UTW configuration. Although the decayer nozzles were effective in reducing the impingement velocity and thus jet/flap interaction noise, they were found to be quite heavy and to introduce internal pressure losses. These disadvantages combined to produce a significant operating cost penalty, with the net effect that the decayer nozzle was not considered attractive for the QCSEE UTW application (ref. 59). Excitation has the potential of providing the same noise reduction in a simpler, less costly manner.

Another example can be drawn from the QCSEE Program, where the OTW nozzle design (fig. 11) required so much compromise and complexity to promote mixing and jet attachment for takeoff and landing with high flap angles that the cruise performance was degraded (ref. 60). The potential of excitation to promote mixing and to control separation might be quite useful in such applications.

V/STOL and STOVL Ground Effects

Increased mixing and spreading rates may also be useful in reducing ground effects for vertical and short takeoff and landing (V/STOL) and short takeoff, vertical landing (STOVL) aircraft, as illustrated in figure 12. Since the exhaust is directed toward the ground, enhanced mixing might reduce ground heating and erosion. Such applications are of crucial importance for tactical aircraft that may be required to land on ships and/or on soft grounds such as desert areas.

Ejectors

Ejector performance may also be improved by enhanced mixing, as illustrated in figure 13. One of the prime causes of poor ejector performance is incomplete mixing. The benefits of enhanced mixing can be achieved in at least two ways:

(1) An ejector with good performance could achieve the same performance in a shorter length, leading to size and weight savings.

(2) An ejector with poor performance could be improved by the increased mixing.

The potential to enhance mixing acoustically is certainly consistent with Quinn's observation of enhanced mixing in the presence of screech tones (refs. 61 and 62).

Internal Mixers

Internal mixer nozzles, such as that sketched in figure 14, are used to increase thrust, improve fuel economy, and reduce noise for turbofan engines. Current mixers achieve good performance with complex geometries, but they incur a weight penalty due to the mixer hardware and the increased outer cowl length. Enhanced mixing due to excitation has the potential to achieve equal or better mixing with simpler (lower cost, easier maintenance) mixer designs or to reduce mixing length to allow a shorter cowl, resulting in weight savings.

Combustors

There are at least two ways enhanced mixing may be applied to combustors, as shown in figure 15: improved fuel/air mixing, leading to shorter combustors (or increased efficiency) along with the possibility of improved pollution control; and improved mixing of the combustion products with the dilution/cooling air leading to a reduction in the pattern factor (or peak-to-average temperature ratio). Preliminary successful experiments on the latter application have been reported by Vermeulen, et al. (ref. 63).

Supersonic Jet Noise Reduction

In supersonic jets the large scale coherent structure plays a strong role in the noise generation processes. Interaction of the large scale structure with shocks is the source of shock noise (e.g., see ref. 64). Large scale structures convecting at supersonic speeds also radiate noise directly (e.g., see ref. 65). High frequency ($S_e > 1.5$) excitation could be used to promote coherent structure formation preferentially at smaller scale, thereby reducing the mixing rate as illustrated in figure 16 and reducing the intensity of the radiated noise.

Separation Control

Separated surface flows degrade the performance of many devices. Attached flows require that the necessary energy be supplied to the boundary layer to overcome adverse pressure gradients, viscous dissipation along the flow path, and energy loss due to momentum exchange. The critical region is near the surface, where the momentum and energy of the local flow is much less than in the outer regions. When the losses are sufficiently high, the flow separates from the surface. To avoid these problems, component shapes are designed to maintain a high energy level near the surface. In some cases the energy level near the surface is augmented by means of vortex generators, blowing or suction, and mechanical vibration. Aeroacoustic excitation may provide an attractive alternative means of controlling separation to improve the performance of wings, flaps, turbomachinery blades, diffusers, transition ducts, inlets and other components and devices. Considering diffusers as an example, high losses and poor flow quality due to incipient and unsteady separation are widely recognized as major problems for wind tunnels. Acoustic excitation may provide an attractive alternative, since it has been shown to greatly improve flow over a wing at high angle of attack (ref. 30). Goldstein (ref. 66) has shown that this is due to enhanced mixing between the high-velocity flow and the separated region, which energizes the boundary layer in somewhat the same manner as the conventional approaches.

Stall Prevention/Recovery

Stall, or loss of lift due to flow separation, is a concern for flow over airfoils and rotating machinery blades because it can lead to catastrophic failures. Several tragic accidents have occurred in recent years when commercial airliners have encountered severe wind shear near the ground. In such cases wing stall often occurs; in fact, one method of surviving a wind shear encounter is to increase the angle of attack toward stall to avoid crashing. Since excitation has been shown to promote attachment (Ahuja, et al., ref. 30), it may very well be applicable to this very important performance and safety problem.

Enhanced Maneuverability

Aeroacoustic excitation could provide enhanced maneuverability for fighter aircraft in several ways. Attachment could be effectively maintained over a widened range of angle of attack, and reasonable lift could be maintained even with some regions separated. Wing rock, due to asymmetric vortices, might be controlled by exciting preferred, and symmetric, vortex structures. Inlet flow attachment could be maintained over a wider angle of attack range.

Skin Friction Reduction

Reduction of skin friction by high-frequency excitation (e.g., as shown by Ahuja, et al., ref. 30) may prove applicable to many internal and external flows, including many potential nonaerospace applications.

Impingement Control

Retarded mixing through high-frequency excitation may prove useful in preventing exhaust impingement on the fuselage and control surfaces.

TECHNOLOGY NEEDS

In order to realize the potential benefits resulting from the engineering applications of acoustic excitation, it will be necessary to carry out a significant applied research effort and to augment the basic research effort. Most of the experimental research has been conducted with small models at near ambient temperature, low Reynolds number, and low Mach number.

High Reynolds Number and High Mach Number

A number of potential applications deal with the control of jet mixing processes in both free and confined geometries. The range of experimental results available for conical nozzle jet mixing control is shown in figure 17, where jet Mach number is plotted against jet Reynolds number for various values of excitation Strouhal number. A map of conditions for which mixing enhancement was observed, as indicated by potential core length reduction, is shown in figure 17(a), and a similar map for jet noise amplification is shown in figure 17(b); these two cases are both examples of augmented mixing. Mixing suppression conditions are mapped in figure 17(c) for jet potential core lengthening and in figure 17(d) for jet noise suppression. The area in the upper right-hand corner is the range of interest for full-scale jet engine applications; very little data has been obtained in this range. This void will have to be filled with experimental data and/or with well validated theoretical or numerical models to allow the development of practical applications.

Threshold Level

Figure 17 addresses only the excitation frequency, through the Strouhal number, and not the level of excitation required to produce the desired effect. The peak turbulent kinetic energy normalized by the ideally expanded jet kinetic energy is plotted against excitation level in figure 18 for three different nozzle pressure ratios at an excitation Strouhal number of 0.5, where enhanced mixing is expected. The theory of Morris and Tam (ref. 25), shown by the solid lines, indicates that as excitation level is increased beyond a certain value the peak turbulent kinetic energy beings to increase, indicating a significant coupling of the excitation signal with the flow field. This minimum, or "threshold," excitation level is seen to increase with increasing nozzle pressure ratio (and therefore with increasing Mach number). The experimental results of Moore (ref. 69) for the threshold level required for jet noise amplification are shown to agree well with theory.

High Temperature

The results shown in figure 18 are for an unheated jet, leaving the issue of temperature effects to be resolved. As temperature is increased at a fixed Mach number, the jet dynamic pressure remains constant but the kinetic energy is increased, while the jet Reynolds number and jet-to-ambient density ratio are decreased; boundary layer conditions are also changed. It is not clear from the literature how the threshold level should be affected by increased temperature. The Morris-Tam theory (ref. 25) indicates that the effects should be minor but the limited experimental results are somewhat conflicting. Some recent results from reference 31 are shown in figure 19. The ratio of the jet centerline Mach number with excitation to its value without excitation at $X/D_j = 9$ is shown as a function of excitation level L_e for four different temperatures at a jet Mach number of $M_j = 0.8$ and at the most sensitive Strouhal number. The excitation level at which the Mach number ratio beings to decrease should roughly correspond to the threshold level. As can be seen, this threshold level increases significantly with increasing temperature.

If we assume that the threshold level is reached when the ratio of the imposed disturbance to the natural disturbance reaches some critical value, then

$$\frac{V_e(T_{j,2})}{V_{un}(T_{j,2})} = \frac{V_e(T_{j,1})}{V_{un}(T_{j,1})} \tag{3}$$

Considering the relation between this imposed velocity disturbance and the imposed pressure disturbance,

$$V_e = p_e/\rho c \tag{4}$$

We obtain then

$$\frac{p_e(T_{j,2})}{p_e(T_{j,1})} = \frac{\rho(T_{j,1})\ c(T_{j,1})}{\rho(T_{j,2})\ c(T_{j,2})} \frac{V_{un}(T_{j,2})}{V_{un}(T_{j,1})} \tag{5}$$

Considering the definition of turbulence intensity $I = v/V$ and the variation of properties with temperature at constant Mach number we obtain

$$\frac{p_e(T_{j,2})}{p_e(T_{j,1})} = \frac{T_{j,2}}{T_{j,1}} \frac{I(T_{j,2})}{I(T_{j,1})} \tag{6}$$

Or in terms of excitation level,

$$L_e(T_{j,2}) - L_e(T_{j,1}) = 20 \log (T_{j,2}/T_{j,1}) + 20 \log \frac{I(T_{j,2})}{I(T_{j,1})} \qquad (7)$$

Neglecting the effect of temperature on turbulence intensity, the threshold level should increase as $20 \log (T_{j,2}/T_{j,1})$. The results of figure 19 are replotted in figure 20 in terms of a corrected excitation level $L_e - 20 \log (T_j/T_a)$. This seems to correlate the data reasonably well except at the highest temperature. Some of the remaining differences could be due to changes in turbulence intensity.

Turbulence Intensity

Figure 21 shows the turbulence intensity as a function of nondimensional axial distance for two temperatures at $M_j = 0.78$. Although there is only a small difference in the peak turbulence intensities, the turbulence intensity near the nozzle lip is considerably higher for the higher temperature case. Since the strongest interactions occur near the nozzle exit, the effect of turbulence intensity should be evaluated there. It appears that the turbulence intensity near the nozzle is at least doubled for the higher temperature case, which would correspond roughly to $I \propto T_j^{2/3}$. Carrying this on to the effect of excitation level would then yield the relation,

$$L_e\,(T_{j,2}) - L_e\,(T_{j,1}) = 35 \log (T_{j,2}/T_{j,1}) \qquad (8)$$

To test this interpretation, the data of figure 19 is again replotted, this time against $L_e - 35 \log (T_j/T_a)$ in figure 22. The data appear to collapse reasonably well, especially in terms of the threshold level, the level at which the Mach number ratio deviates from unity, which appears to be within about ±2 dB. This should not be considered as a general correlation because the data are limited to only one jet Mach number and one size, but it does indicate that a systematic relationship can be developed. Not only should threshold data be obtained over a more extensive range, but turbulence intensity information is also needed.

Experimental Capability Enhancement

In order to perform the needed high-temperature, high-velocity experiments, the hot coaxial jet facility at NASA Lewis (fig. 23) is currently being modified for excitation research by installing an eight-driver spool piece upstream of the nozzle. (This facility has been used extensively for jet noise research and is described in ref. 71.) The facility provides jet temperatures up to 1100 K and can accommodate nozzles having total equivalent diameters up to 20 cm. The eight drivers can be driven to produce higher order circumferential modes as well as plane waves which have been used in most of published studies on acoustic excitation. Jet plume mean velocity and temperature profiles will be obtained in the near term, and we hope to install turbulence and diagnostic instrumentation in the future. We are also installing a four-driver excitation system in the jet rig used for the turbulence studies of Laurence (ref. 72), to enable us to obtain more detailed data on smaller (8.8-cm diam) unheated jets.

Another area which needs investigation is the method of introducing the excitation signal. We have devoted most of our attention to upstream excitation (fig. 24(a)) where the acoustic signal is introduced into the flow upstream of the nozzle. This approach is limited by the transmission characteristics of the geometry. In order to produce the desired effect in high velocity, high temperature jets it may be more efficient to introduce the excitation externally, perhaps near the nozzle lip as shown in figure 23(b). This method has been successfully employed, for example by Kibens (refs. 73 and 74).

CONCLUDING REMARKS

From the results presented and reviewed in this paper it is clear that acoustic excitation shows great promise as a means of controlling shear flows. However, there are many gaps in our fundamental understanding of the unsteady aerodynamic process involved and in applications know-how. To address these problems we have initiated fundamental experimental, theoretical and numerical studies. We are also conducting preliminary studies to identify those applications exhibiting the greatest potential.

APPENDIX - SYMBOLS

A	area
C	wing chord
c	sonic velocity
D	diameter
f	frequency
I	turbulence intensity, $\sqrt{v^2}/V$
L	sound pressure level, dB re 20 $\mu N/m^2$
ℓ	characteristic length
M	Mach number, V/c
P	pressure (mean component, total)
p	fluctuating pressure
R	source-to-observer distance
Re	Reynolds number, $\ell V \rho/\mu$
T	temperature (total)
V	velocity (mean component)
v	fluctuating velocity
μ	viscosity
ρ	density

Subscripts:

a	ambient
e	excitation
ex	excited
i	impingement
j	jet (ideally expanded)
p	peak value
un	unexcited
0	freestream
1,2	arbitrary conditions

REFERENCES

1. Crow. S. C. and Champagne, F. H., "Orderly Structure in Jet Turbulence," Journal of Fluid Mechanics, Vol. 48, Part 3, 1971, pp. 547-591.
2. Winant, C. D. and Browand, F. K., "Vortex Pairing: The Mechanism of Turbulent Mixing-Layer Growth at Moderate Reynolds Number," Journal of Fluid Mechanics, Vol. 63, 1974, pp. 237-255.
3. Brown, G. L. and Roshko, A., "On Density Effects and Large Structures in Turbulent Mixing Layers," Journal of Fluid Mechanics, Vol. 64, 1974, pp. 775-816.
4. Roshko, A., "Structure of Turbulent Shear Flows: A New Look," AIAA Journal, Vol. 14, No. 10, Oct. 1976, pp. 1349-1357.
5. Hussain, A. K. M. F. and Zaman, K. B. M. Q., "Effect of Acoustic Excitation on the Turbulent Structure of a Circular Jet," Third Interagency Symposium on University Research in Transportation Noise, University of Utah, Sal Lake City, Utah, 1975, pp. 314-326.
6. Hussain, A. K. M. F. and Thompson, C. A., "Controlled Symmetric Perturbation of the Plane Jet: An Experimental Study in the Initial Region," Journal of Fluid Mechanics, Vol. 100, Part 2, 1980, pp. 397-431.
7. Wygnanski, I., Oster, D., Fiedler, H., and Dziomba, B., "On the Perserverence of a Quasi-Two-Dimensional Eddy Structure in a Turbulent Mixing Layer," Journal of Fluid Mechanics, Vol. 93, 1979, pp. 325-335.
8. Hussain, A. K. M. F., "Conerent Structures - Reality and Myth," Physics of Fluids, Vol. 26, No. 10, Oct. 1983, pp. 2816-2850.
9. Tyndall, J., "On the Action of Sonorous Vibration on Gaseous and Liquid Jets," Philosophical Magazine, Vol. 33, 1867, pp. 375-391
10. Rayleigh, Lord J. W. G., "On the Instability of Jets," Scientific Papers I, Cambridge Univ. Press, 1878, pp. 361-371.
11. Brown, G. B., "On Vortex Motion in Gaseous Jets and the Origin of Their Sensitivity to Sound," Physical Society of London Proceedings, Vol. 47, 1935, pp. 703-732.
12. Chanaud, R. C. and Powell, A., "Experiments Concerning the Sound-Sensitive Jet," Acoustical Society of America. Journal, Vol. 34, 1962, pp. 907-915.
13. Vlasov, E. V. and Ginevskii, A. S., "Acoustic Modification of the Aerodynamic Characteristics of a Turbulent Jet," Izv. AN SSSR, Mekhanika Zhidkosti i Gaza Vol. 2, 1967, pp. 133-138.
14. Glass, D. R., "Effects of Acoustic Feedback on the Spread and Decay of Supersonic Jets," AIAA Journal, Vol. 6, 1968, pp. 1890-1897.
15. Simcox, C. D., "A Theoretical Investigation of Acoustic-Turbulence Interactions with Application to Free-Jet Spreading," Ph.D. Thesis, Purdue University, 1969.
16. Hribar, A. E., "On the Interaction of Intense Acoustic Fields and Viscous Fluid Flows," Journal of Basic Engineering, Vol. 91, 1969, pp. 74-80.
17. Lebedev, N. G. and Telenin, G. F., "Interaction Between a Supersonic Jet and an Acoustic Field," Izv. AN SSSR, Mekhanika Zhidkosti i Gaza, Vol. 4, 1970, pp. 82-94.
18. Simcox, C. D. and Hoglund, R. F., "Acoustic Interactions with Turbulent Jets," Journal of Basic Engineering, Vol. 93, 1971, pp. 42-46.
19. Morkovin, M. V. and Paranjape, S. V., "On Acoustic Excitation of Shear Layers," Zeitschriftfuer Flugwissenschaften, Vol. 19, 1971, pp. 328-335.
20. Rockwell, D. O. and Toda, K., "Effects of Applied Acoustic Fields on Attached Jet Flows," Journal of Basic Engineering, Vol. 93, 1971, pp. 63-73.

21. Goldschmidt, V. W. and Kaiser, K. F., "Interaction of an Acoustic Field and a Turbulent Plane Jet: Mean Flow Measurements," AIChE Chem. Eng. Prog. Symp. Ser., Vol. 67, 1971, pp. 91-98.
22. Borisov, Y. Y. and Rosenfeld, E. I., "Action of Acoustic Oscillations on Flow Stability and Structure," Soviet Physics-Acoustics, Vol. 17, 1971, pp. 154-168.
23. Hussain, A. K. M. F. and Thompson, C. A., "Controlled Systematic Perturbation of the Plane Jet: An Experimental Study in the Initial Region," Journal of Fluid Mechanics, Vol. 110, 1981, pp. 397-431.
24. Hussain, A. K. M. F. and Zaman, K. B. M. Q., "The 'Preferred Mode' of the Axisymmetric Jet," Journal of Fluid Mechanics, Vol. 110, 1981, pp. 39-71.
25. Ahuja, K. K., Lepicovsky, J., Tam, C. K. W., Morris, P. J. and Burrin, R. H., "Tone-Excited Jets -- Theory and Experiments," NASA CR-3538, No. 1982.
26. Goldstein, M. E., "The Coupling Between Flow Instabilities and Incident Disturbances at a Leading Edge," Journal of Fluid Mechanics, Vol. 104, 1981, pp. 217-246.
27. Tam, C. K. W. and Block, P. J. W., "Excitation of Instability Waves in a Two-Dimensional Shear Layer by Sound," Journal of Fluid Mechanics, Vol. 89, 1978, pp. 373-399.
28. Crighton, D. G. and Gaster, M., "Stability of Slowly Diverging Jet Flow," Journal of Fluid Mechanics, Vol. 77, 1976, pp. 397-413.
29. Gaster, M., Kit, E. and Wygnanski, I., "Large-Scale Structures in a Forced Turbulent Mixing Layer," Journal of Fluid Mechanics.
30. Ahuja, K. K., Whipkey, R. R. and Jones, G. S., "Control of Turbulent Boundary Layers by Excitation," AIAA Paper No. 83-0726, Apr. 1983.
31. Lepicovsky, J., Ahuja, K. K., Salikuddin, M., and Morris, P. J., "Tone-Excited Heated Jets," Part 1. Report No. LG84ER0032, Lockheed-Georgia Co., June 1984.
32. von Glahn, U. H., "Correlationof Flight Effects on Centerliune Velocity Decay for Cold-Flow Acoustically Excited Jets," NASA TM-83502, Nov. 1983.
33. von Glahn, U. H., "On Some Flow Characteristics of Conventioinal and Excited Jets," AIAA Paper No. 84-0532, Jan. 1984 (also NASA TM-83503).
34. Hasan, M. A. Z. and Hussain, A. K. M. F., "The Self-Excited Axisymmetric Jet," Journal of Fluid Mechanics, Vol. 115, Feb. 1982, pp. 59-89.
35. Borisov, Yu. Ya. and Gynkina, N. M., "Acoustic Excitation of High-Velocity Jets," Soviet Physics-Acoustics, Vol. 21, No. 3, May-June 1975, pp. 230-233.
36. Vulis, L. A., "Turbulent Mixing of Free Gas Jets," Fluid Mechanics-Soviet Research, Vol. 1, No. 3, May-June 1972, pp. 130-135.
37. Vlasov, Ye. V., Ginevskiy, A. S. and Ukhanova, L. N., "Teplomassobmen V Zatoplennykh Turbulentnykh Stuyakh V Pole Zvukovykh Kolebaniy," Heat and Mass Transfer, Proceedings of the 5th All-Union Conference on Heat and Mass Transfer, Naukova dumka Pres, Kiev, Vol. 1, Pt. 2, 1976, pp. 187-191.
38. Schmidt, C., "Aerodynamic Characterization of Excited Jets," Journal of Sound and Vibration, Vol. 61, No. 1, Nov. 1978, pp. 148-152.
39. Morris, P. J. and Baltas, C., "Turbulence in Sound Excited Jets: Measurement and Theory," AIAA Paper No. 81-0058, Jan. 1981.
40. Seiner, J. M., McLaughlin, D. K. and Liu, C. H., "Supersonic Jet Noise Generated by Large-Scale Instabilities," NASA TP-2072, Sept. 1982.
41. Dorsch, R. G., Clark, B. J. and Reshotko, M., "Interim Prediction Method for Externally Blown Flap Noise," NASA TM X-71768.
42. Dorsch, R. G., Krejsa, E. A. and Olsen, W. A., "Blown Flap Noise Research," AIAA Paper No. 71-745, June 1971.

43. Olsen, W. A., Dorsch, R. G. and Miles, J. H., "Noise Produced by a Small-Scale Externally Blown Flap," NASA TN D-6636, 1972.
44. Dorsch, R. G., Lasagna, P. L., Maglieri, D. J. and Olsen, W. A., "Flap Noise," Aircraft Engine Noise Reduction, NASA SP-311, 1972, pp. 259-290.
45. Olsen, W. A., Miles, J. H. and Dorsch, R. G., "Noise Generated by Impingement of a Jet Upon a Large Flat Board," NASA TN D-7075, 1972.
46. Dorsch, R. G., Goodykoontz, J. H. and Sargent, N. B., "Effect of Configuration Variation on Externally Blown Flap Noise," AIAA Paper No. 74-190, Jan.-Feb. 1974.
47. Clark, B. J., Dorsch, R. G. and Reshotko, M., "Flap Noise Prediction Method for a Powered Lift System," AIAA Paper No. 73-1028, Oct. 1973.
48. Miles, J. H., "Rational Function Representation of Flap Noise Spectra Including Correction for Reflection Effects," AIAA Paper No. 74-193, Jan.-Feb. 1974.
49. Dorsch, R. G., Reshotko, M. and Olsen, W. A., "Flap Noise Measurements for STOL Configurations Using External Upper Surface Blowing," AIAA Paper No. 72-1203, Nov.-Dec. 1972.
50. Reshotko, M. and Friedman, R., "Acoustic Investigation of the Engine-Over-the-Wing Concept Using a D-Shaped Nozzle," AIAA Paper No. 73-1030, Oct. 1973.
51. McKinzie, D. J., Jr., "Measured and Predicted Impingement Noise for a Model-Scale Under-the-Wing Externally Blown Flap Configuration With a QCSEE-Type Nozzle," NASA TM-81494, June 1980.
52. Chestnutt, D., Maglieri, D. J. and Hayden, R. E., "Flap Noise Generation and Control," STOL Technology, NASA SP-320, 1972, pp. 413-426.
53. von Glahn, U. H., Grosebeck, D. E. and Huff, R. G., "Peak Axial-Velocity Decay with Single- and Multi-Element Nozzles," AIAA Paper No. 72-48, Jan. 1972.
54. Goodykoontz, J. H., Dorsch, R. G. and Groesbeck, D. E., "Noise Tests for a Mixer Nozzle - Externally Blown Flap System," NASA TN D-7236, 1973.
55. McKinzie, D. J., Jr. and Burns, R. J., "Externally Blown Flap Trailing Edge Noise Reduction by Slot Blowing - A Preliminary Study," AIAA Paper No. 73-245, Jan. 1973.
56. McKinzie, D. J., Jr., "Aeroacoustic Performance of an Externally Blown Flap Configuration with Several Flap Noise Suppression Devices," NASA TP-1995, May 1982.
57. Hayden, R. E., "Fundamental Aspects of Noise Reduction from Powered-Lift Devices," SAE Paper No. 730376, Apr. 1973.
58. Nordstrom, K. E. and Hartke, C. W., "YC-15 Propulsion Integration," Quiet, Powered-Lift Propulsion, NASA CP-2077, Nov. 1978, pp. 365-385.
59. Ciepluch, C., "QCSEE Program Background," Quiet, Powered-Lift Propulsion, NASA CP-2077, Nov. 1978, pp. 1-5.
60. Wesoky, H. L., "QCSEE Over-the-Wing Nozzle and Thrust Reverser Aerodyanmics, Quiet, Powered-Lift Propulsion, NASA CP-2077, Nov. 1978, pp. 175-197.
61. Quinn, B., "Effect of Aeroacoustic Interactions on Ejector Performance," Journal of Aircraft, Vol. 12, Nov. 1975, pp. 914-916.
62. Quinn, B., "Interactions Between Screech Tones and Ejector Performance," Journal of Aircraft, Vol. 14, May 1977, pp. 467-473.
63. Vermeulen, P. J., Odgers, J. and Ramesh, V., "Acoustic Control of Dilution Air Mixing in a Gas Turbine Combustor," Journal of Engineering for Power, Vol. 104, Oct. 1982, pp. 844-852.
64. Tam, C. K. W. and Jackson, J. A., "On the Shock Structure and Noise of Supersonic Jets," AIAA Paper No. 83-0703, Apr. 1983.

65. Ribner, H. S., "Eddy-Mach Wave Noise from a Simplified Model of a Supersonic Mixing Layer," Basic Aerodynamic Noise Research, NASA SP-207, 1969, pp. 53-61.
66. Goldstein, M. E., "Generation of Instability Waves in Flow Separating from Smooth Surfaces," Journal of Fluid Mechanics, Vol. 145, Aug. 1984.
67. Jubelin, B., "New Experimental Studies on Jet Noise Amplification," AIAA Paper No. 80-0961, June 1980.
68. Bechert, D. and Pfizenmaier, E., "On the Amplification of Broadband Jet Noise by a Pure Tone Excitation," AIAA Paper No. 76-489, July 1976.
69. Moore, C. J., "The Role of Shear Layer Instability Waves in Jet Exhaust Noise," Journal of Fluid Mechanics, Vol. 80, Part 2, 1977, pp. 321-367.
70. Zaman, K. B. M. Q. and Hussain, A. K. M. F., "Turbulence Suppression in Free Shear Flows by Controlled Excitation," Journal of Fluid Mechanics, Vol. 103, 1981, pp. 133-159.
71. Goodykoontz, J. H. and Stone, J. R., "Experimental Study of Coaxial Nozzle Exhaust Noise," AIAA Paper No. 79-0631, Mar. 1979.
72. Laurence, J. C., "Intensity, Scale, and Spectra of Turbulence in Mixing Region of Free Subsonic Jet," NACA Report 1292, 1956.
73. Kibens, V., "Discrete Noise Spectrum Generated by an Acoustically Excited Jet," AIAA Journal, Vol. 18, No. 4, April 1980, pp. 434-441.
74. Kiebens, V., "The Limits of Initial Shear-Layer Influence on Jet Development," AIAA Paper No. 81-1960, Oct. 1981.

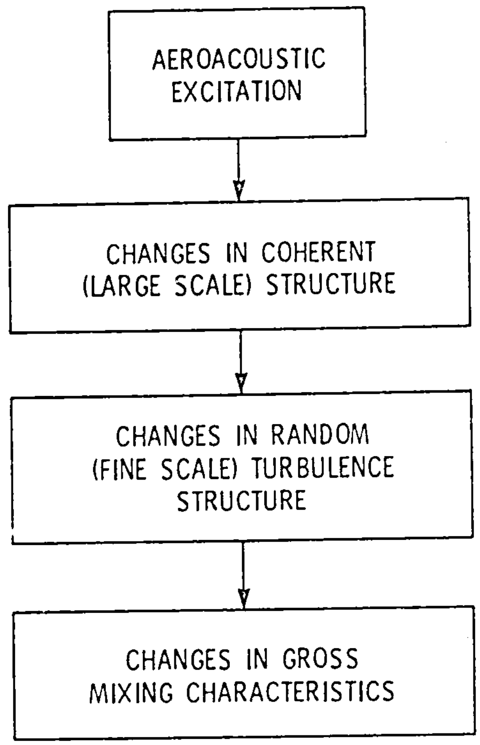
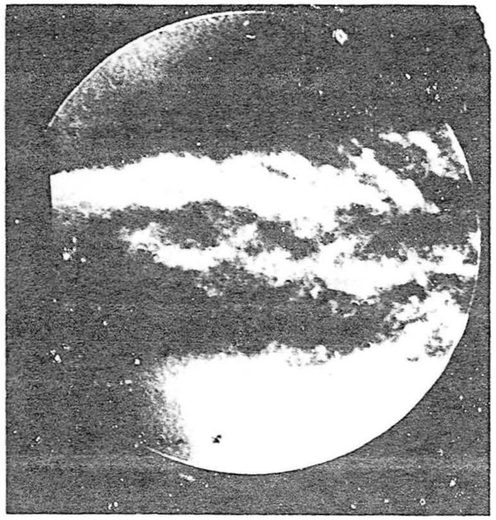


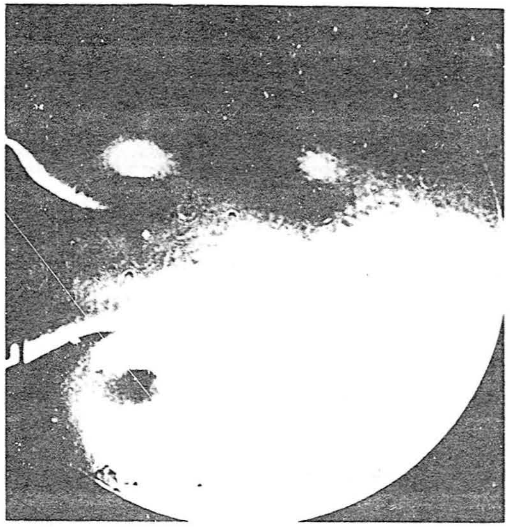
Figure 1. - Aeroacoustic shear layer modification.



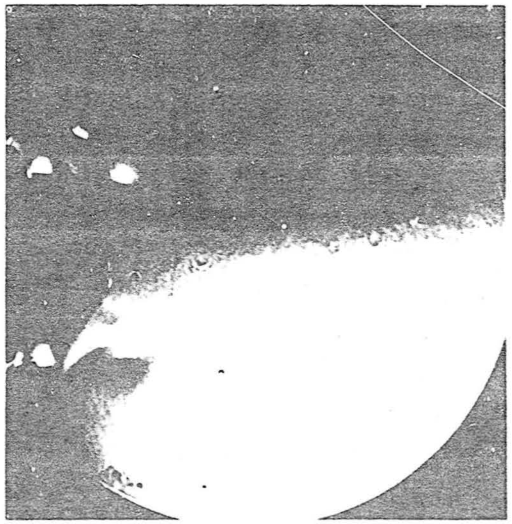
(a) Unexcited.

(b) Excited.

Figure 2. - Upstream acoustic excitation of a jet Schlierin photographs.



(a) Excitation frequency, $f_e = 0.5\ V_j/D_j$.



(b) Excitation frequency, $f = V_j/D_j$.

Figure 3. - Photographically averaged large-scale jet structure.

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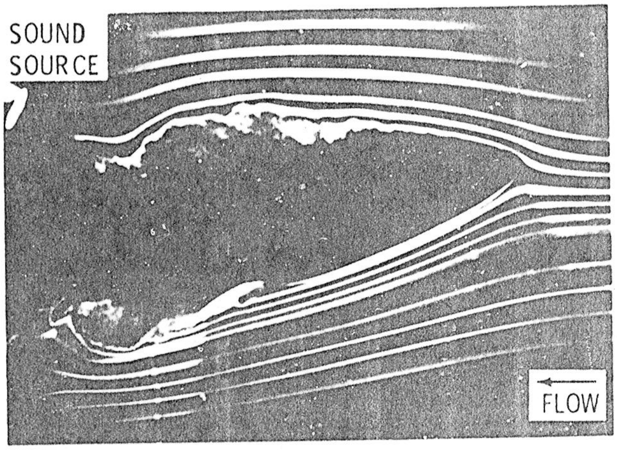
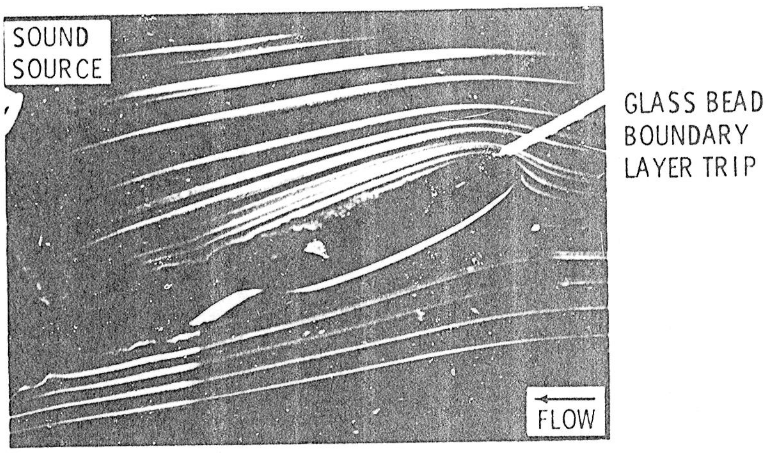


(a) Unexcited.



(b) Excited.

Figure 4. - Effect of acoustic excitation on turbulent boundary layer separation; angle of attack, 26 deg.; free stream velocity, V_0 = 13 m/sec; excitation frequency, f_e = 640 Hz.

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LOW FREQUENCY EXCITATION

- RAPID JET SPREADING FOR EXTERNALLY BLOWN FLAP
  - LIFT ENHANCEMENT
  - FLAP LOADS AND NOISE REDUCTION
- V/STOL GROUND EFFECTS
- EJECTOR IMPROVEMENT BY ENHANCED MIXING
- INTERNAL MIXER SIMPLIFICATION AND WEIGHT REDUCTION
- COMBUSTOR
  - SHORTEN COMBUSTION ZONE
  - IMPROVE MIXING OF PRODUCTS AND COOLANT TO LOWER PEAK METAL TEMPERATURE

HIGH FREQUENCY EXCITATION

- SUPERSONIC JET NOISE REDUCTION

(a) Free shear layer.

LOW FREQUENCY EXCITATION

- SEPARATION CONTROL
  - WINGS
  - TURBOMACHINERY BLADES
  - DIFFUSERS
  - TRANSITION DUCTS
  - INLETS
- STALL PREVENTION/RECOVERY
  - WINGS
  - TURBOMACHINERY BLADES
- ENHANCED MANEUVERABILITY
  - WIDEN α RANGE
  - MINIMIZE WING ROCK

HIGH FREQUENCY EXCITATION

- SKIN FRICTION REDUCTION
- IMPINGEMENT CONTROL

(b) Boundary layer.

Figure 5. - Applications of aeroacoustic flow excitation.

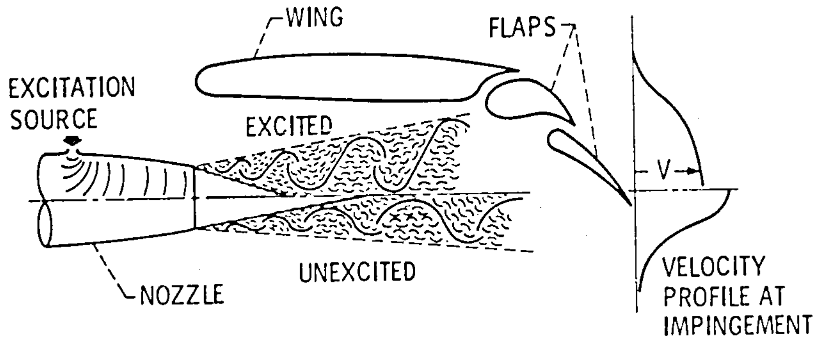

Figure 6. - Rapid jet spreading for under-the-wing externally blown flap.

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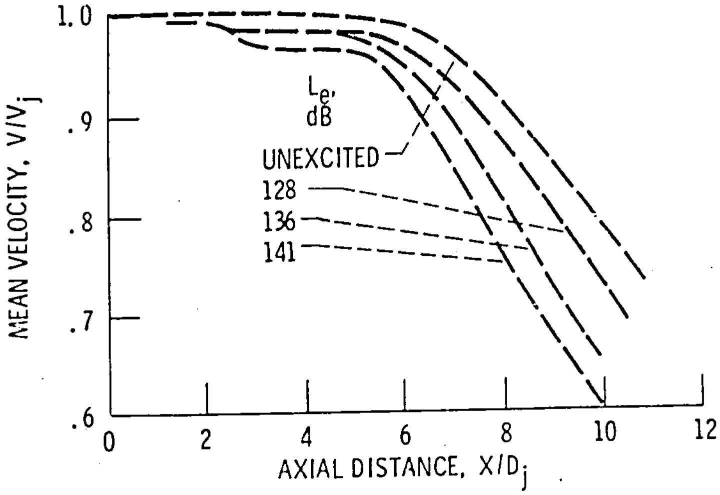
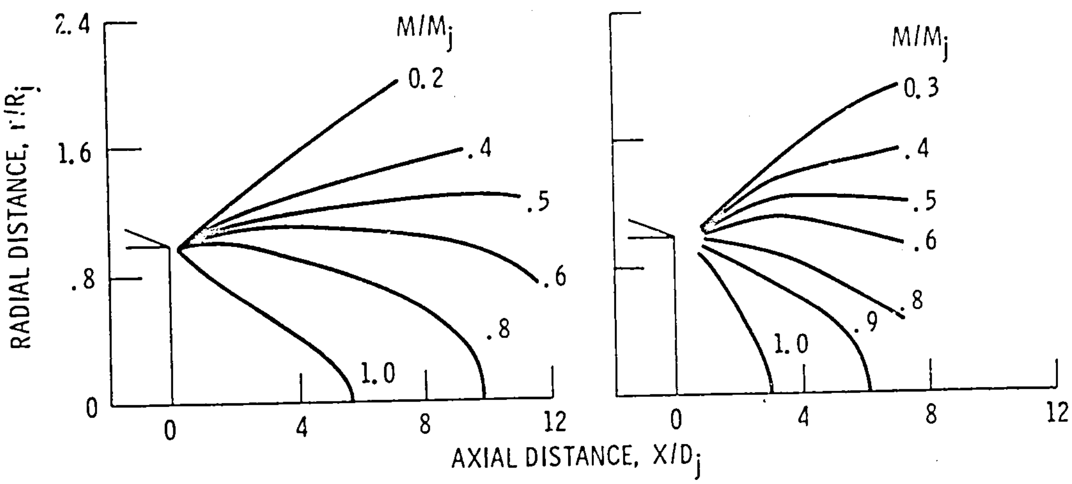


Figure 7. - Excitation-level effects on centerline mean velocity distribution; M_j = 0.58, V_j = 195 m/s, unheated, static, S_e = 0.5 (ref. 25).



(a) Unexcited.

(b) Excited, S_e = 0.5, L_e = 141 dB.

Figure 8. - Mean velocity contours, V_j = 195 m/s, M_j = 0.58, unheated, static (ref. 25).

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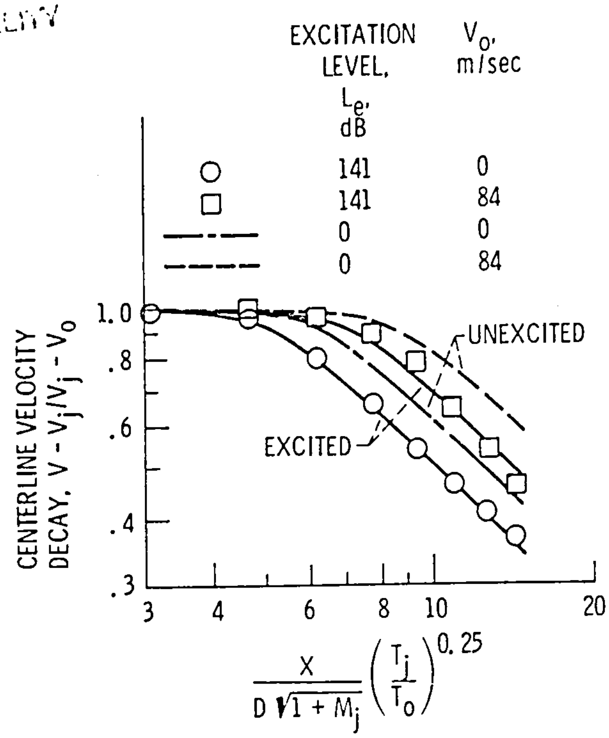

Figure 9. - Effect of flow excitation on centerline velocity decay with and without flight speed. $M_j = 0.58$ (ref. 32).

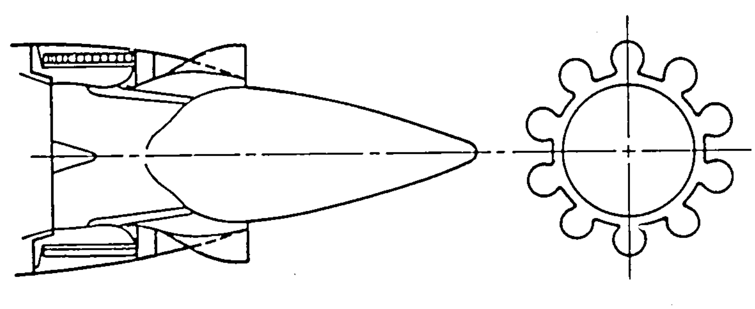

Figure 10. - YC-15 external-mixer decayer nozzle (ref. 58).

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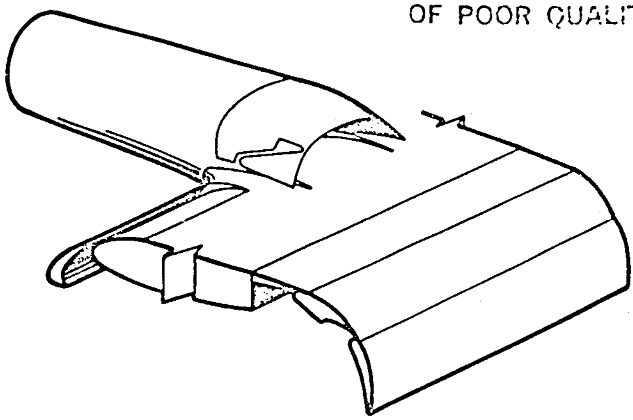

1. REPRESENTATIVE OF A 4-ENGINE AIRCRAFT INSTALLATION, BUT NOT TAILORED TO A SPECIFIC AIRCRAFT DESIGN
2. EXTERNAL FLOW LINES REPRESENTATIVE OF A 0.72 CRUISE MACH NUMBER
3. UPPER SURFACE FLOW ATTACHMENT FOR ALL FLAP POSITIONS
   (a) APPROACH FLAP CHORD LINE ANGLE = 60°
   (b) TAKEOFF FLAP CHORD LINE ANGLE = 30°
4. ABOUT 25-PERCENT AREA VARIATION BETWEEN TAKEOFF AND CRUISE OPERATION

Figure 11. - QCSEE OTW nozzle design objectives (ref. 60).

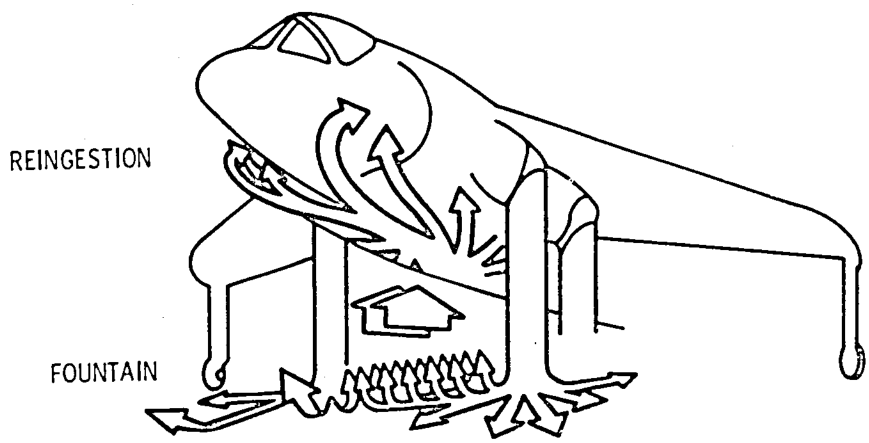

Figure 12. - V/STOL and STOVL ground effects: flow patterns during vertical takeoff and landing.

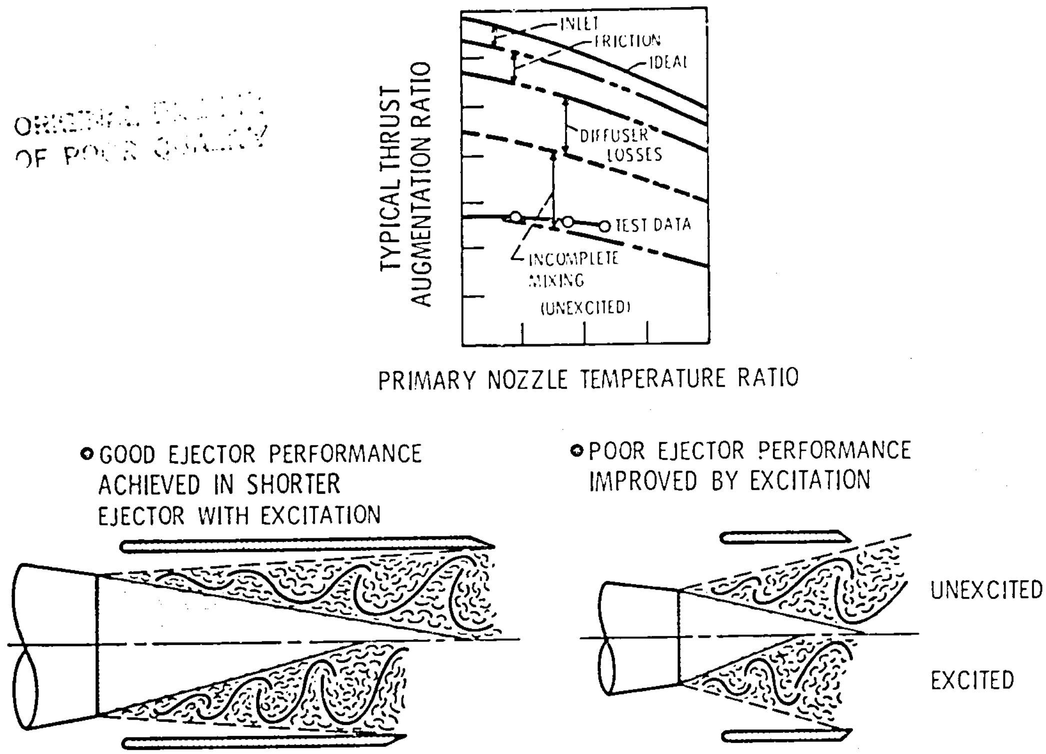

Figure 13. - Ejector performance improvement by enhanced mixing.

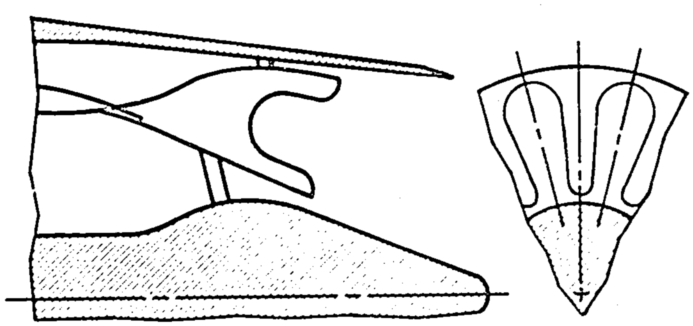

Figure 14. - Internal mixer simplification and weight reduction.

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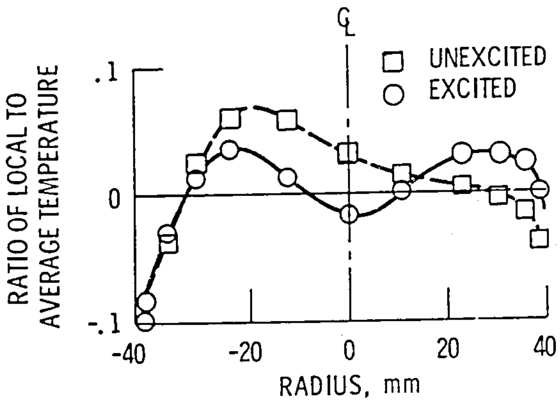
FUEL-AIR

DILUTION AIR - COMBUSTION PRODUCTS

→ SHORTER COMBUSTORS OR INCREASED EFFICIENCY AND/OR POLLUTION CONTROL



→ LOWER METAL PEAK TEMPERATURES

Figure 15. - Aeroacoustic shear layer modification in combustors-enhanced mixing. Combustor exit temperature profile (data of Vermeulen, et al. (ref. 63).

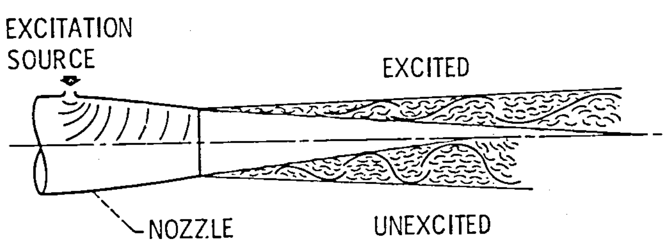


Figure 16. - Supersonic jet noise reduction with high frequency ($S_e > 1.5$) excitation.

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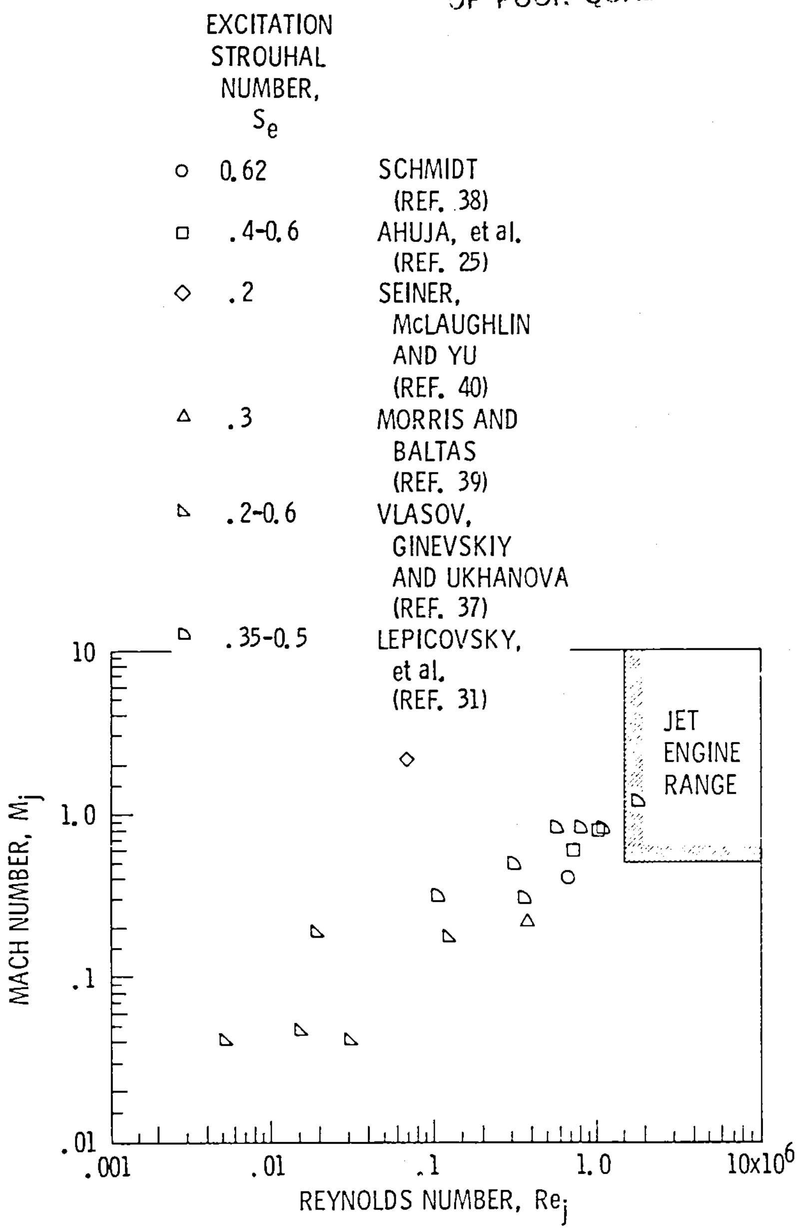
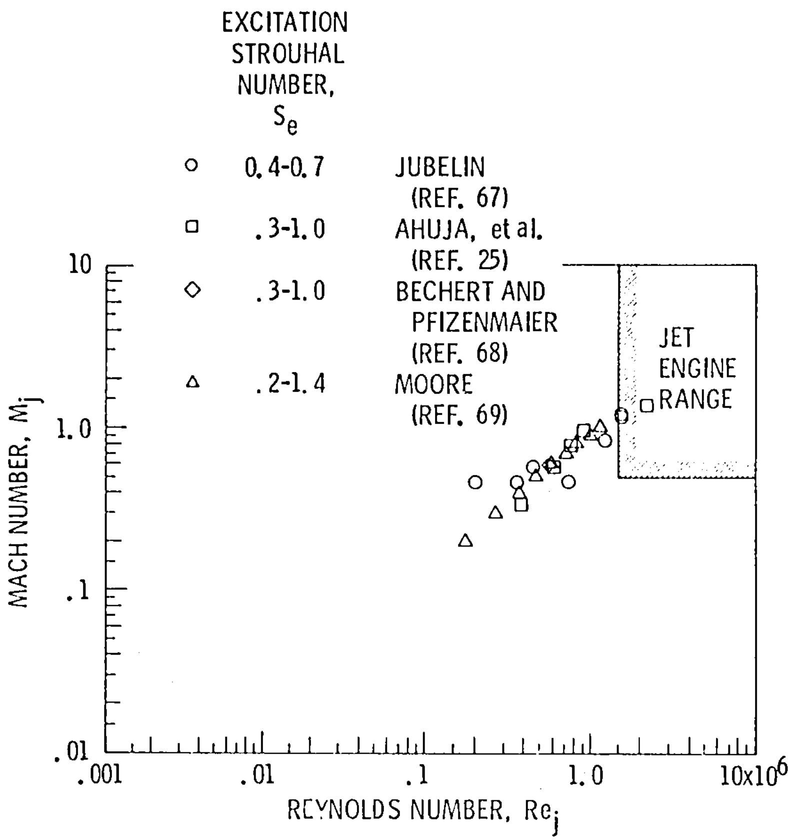


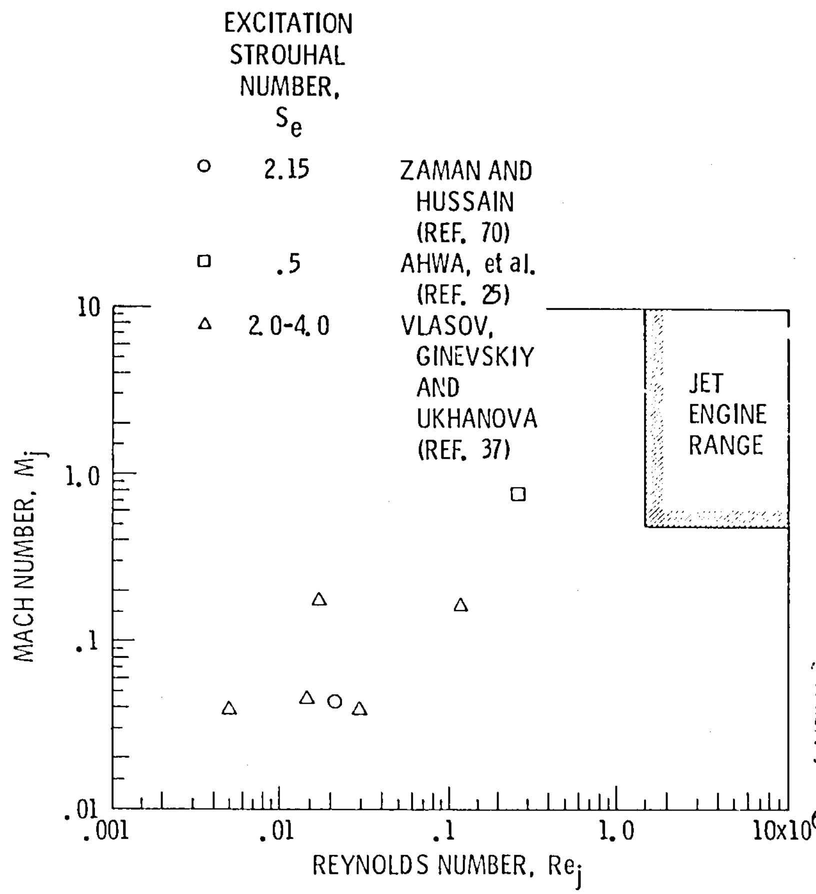
(a) Potential core length reduction.

Figure 17. - Conical nozzle jet excitation experimental conditions.



(b) Acoustic amplification observed.

Figure 17. - Continued.



(c) Potential core length extension.

Figure 17. - Continued.

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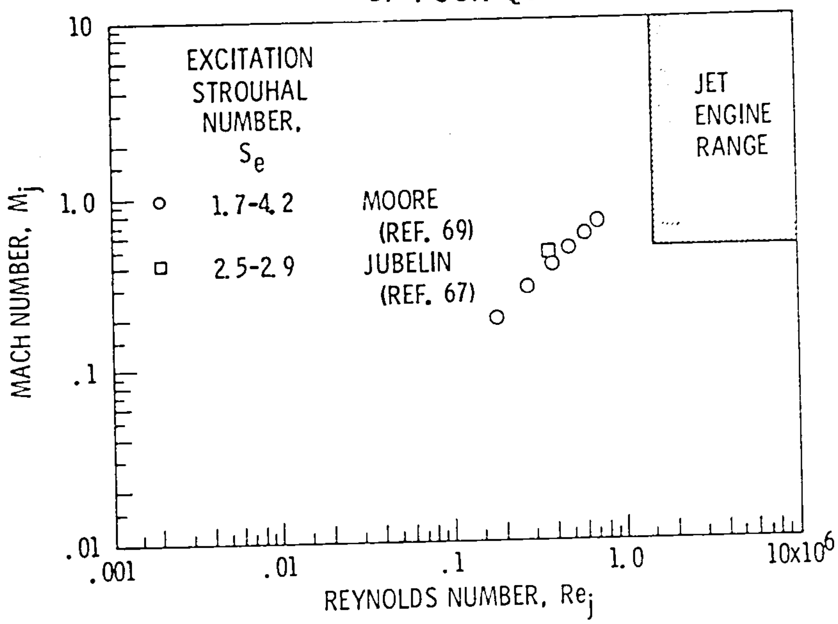

(d) Acoustic suppression observed.

Figure 17. - Concluded.

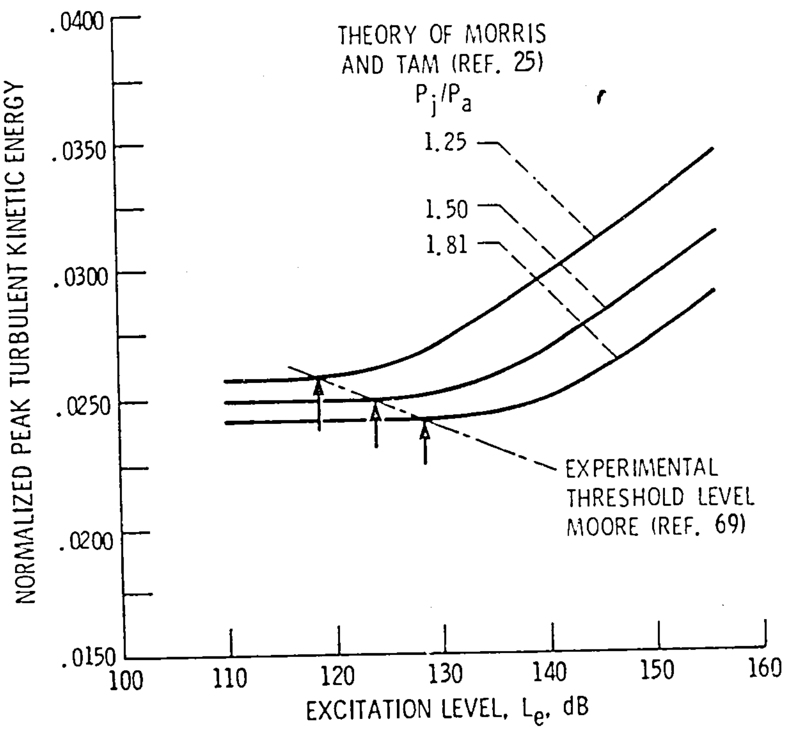

Figure 18. - Effect of excitation level on peak turbulent kinetic energy. Excitation Strouhal number, $S_e = 0.5$; Jet-to-ambient temperature ratio, $T_j/T_a = 1.0$; plane wave mode.

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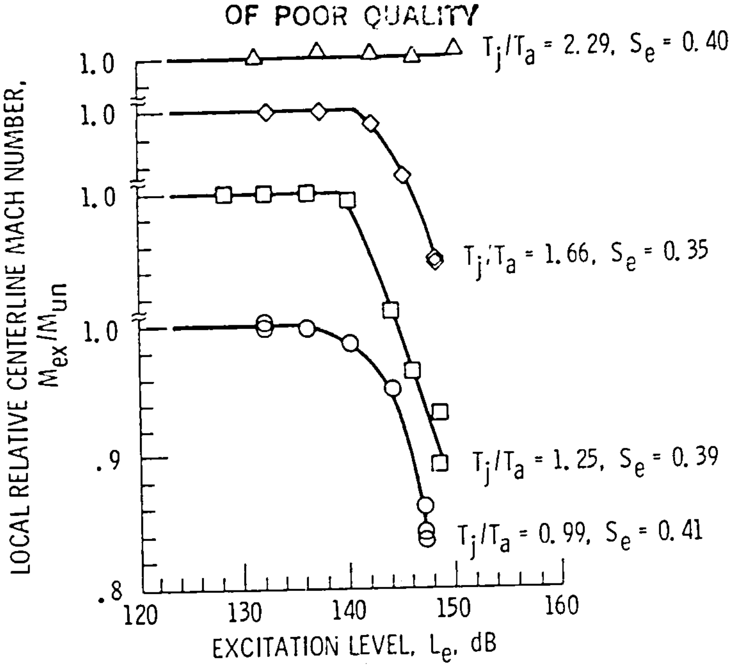

Figure 19. - Effect of excitation level on local relative centerline Mach number at various temperatures at jet exit Mach number, M_j = 0.8, and most-sensitive Strouhal number. Data of Lepicovsky, et al. (ref. 31), X/D_j = 9.0.

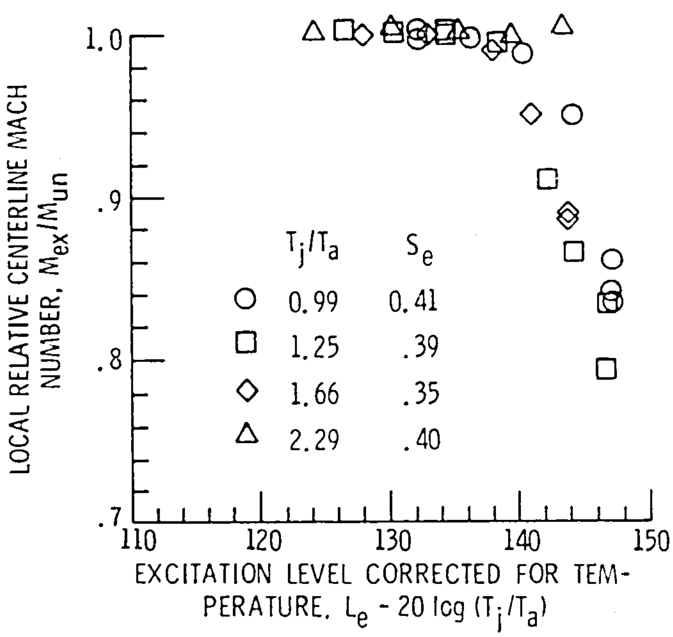

Figure 20. - Effect of excitation level corrected for temperature on local relative centerline Mach number, M_j = 0.8. Data of Lepicovsky, et al. (ref. 31), X/D_j = 9.0.

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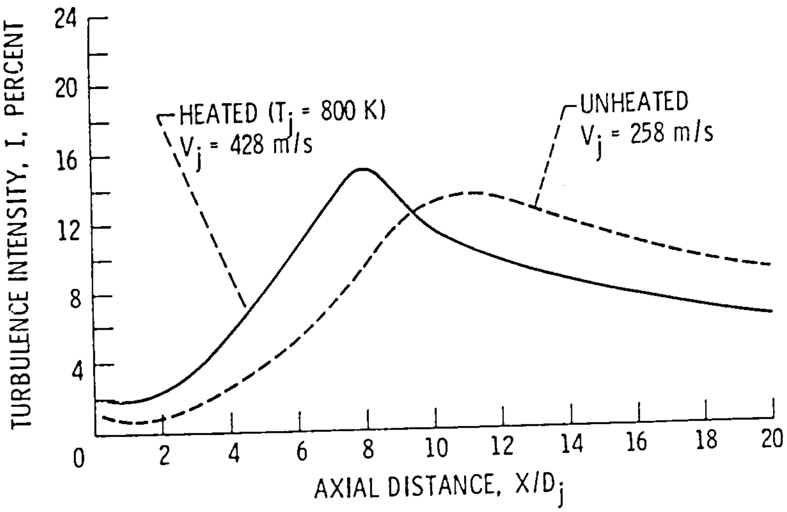

Figure 21. - Temperature effects on centerline distribution of turbulence intensity M_j = 0.78, static, unexcited (ref. 25).

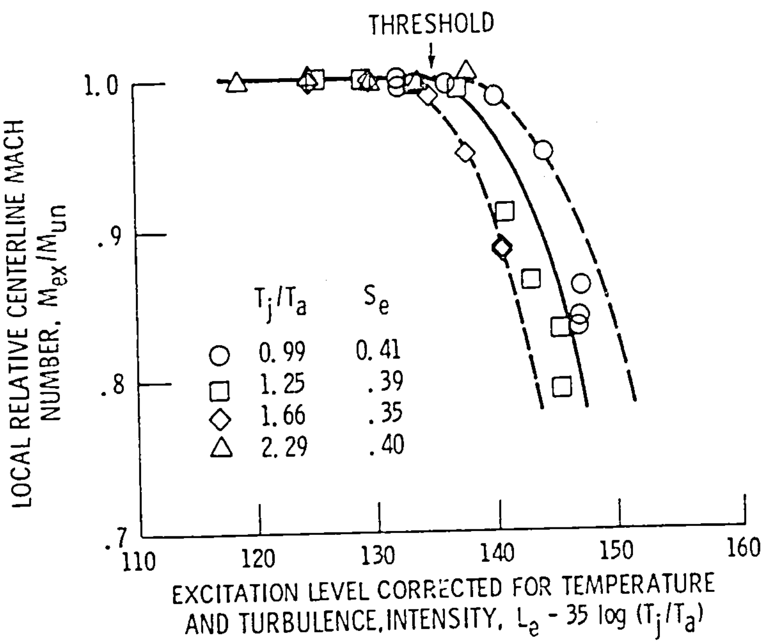

Figure 22. - Effect of excitation level corrected for temperature and turbulence intensity on local relative centerline Mach number, M_j = 0.8. Data of Lepicovsky, et al. (ref. 31), X/D_j = 9.0.

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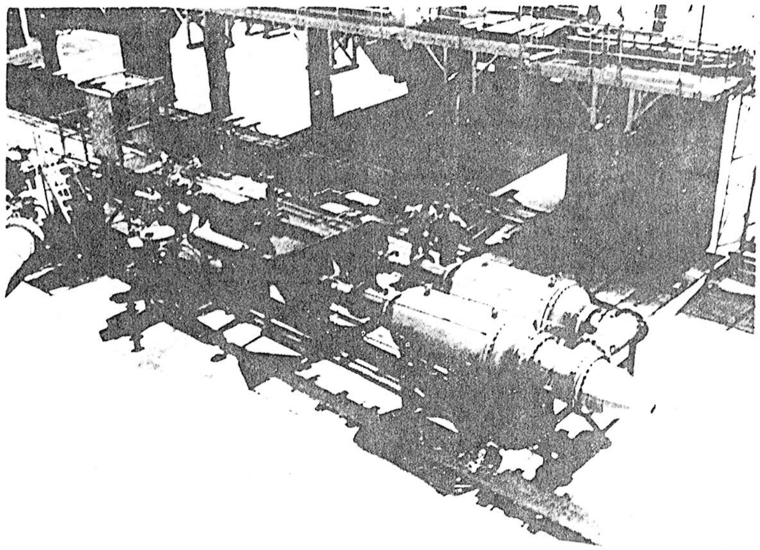

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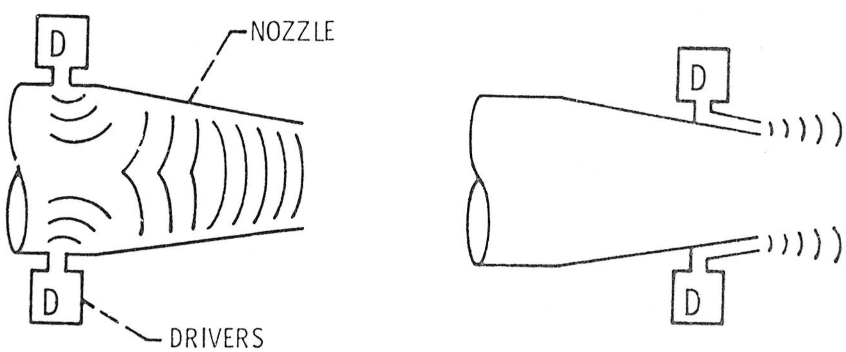
Figure 23. - Coaxial hot jet aeroacoustic excitation facility.



(a) Upstream (internal).

(b) External (nozzle lip).

Figure 24. - Method of introducing excitation signal.

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