Acoustic Control of Free Jet Mixing

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The paper reports a detailed study on the acoustic control of free jet mixing at realistic Reynolds numbers. The experimental results were obtained at Mach numbers of 0.3 and 0.8 and flow total temperatures of up to 800 K. The Reynolds numbers ranged from 350,000 to 1,300,000. Excitation Strouhal numbers were in the range of 0.2-0.6. The experimental results are compared with predictions, based on an extension of the analysis by Tam and Morris. The results showed that proper upstream tone excitation enhances mixing of unheated jets for both high-speed, high Reynolds number conditions and for low-speed conditions. The heated jet, however, shows a response to upstream excitation that depends on jet Mach number. The agreement between the predictions and the experiments is very good for unheated jet conditions. However, for jets heated to temperatures above 600 K, the theoretical predictions differ from the experimental results.

Nomenclature

D = nozzle exit diameter
L = sound pressure level
M = Mach number
Re = Reynolds number
St = Strouhal number
T = temperature
U = velocity
X = axial distance
ϕ = phase shift

Subscripts

e = excitation
ex = excited
j = jet
o = ambient
p = probe
t = total
un = unexcited

Introduction

THE acoustic control of the mixing of a free jet by upstream tone excitation is well documented in the open literature.[1-20] However, the majority of the published studies deal with unheated, low-speed, and low Reynolds number jets.[1-7,10,18-20] Fewer studies have been published on the subject of the effects of acoustic excitation on hot jet mixing.[8,9,11-17] Only Refs. 8, 9, and 13-17 deal with the aerodynamic aspects of tone-excited heated jets. Since hot jet mixing is encountered in many practical applications, further investigation of the potential of hot jet mixing enhancement by means of acoustic excitation is needed.

Method of Approach

The experiments were performed in two phase. The first phase consisted of mean flow measurements to investigate the effect of excitation Strouhal number on jet behavior. The second phase consisted of flow visualization using a unique laser schlieren system developed recently at Lockheed.[20] Phase-locked flow pictures were taken for those flow conditions that showed significant modifications due to upstream tone excitation. The results of the experimental tasks were compared with the theoretical results[8,15] in terms of the relationships between the excitation characteristics and changes in the mean flowfield of the jet.

Test Facility

The experiments were carried out in Lockheed's jet-flow facility shown in Fig. 1. The flow in this facility may be heated by a through-flow propane burner up to 1000 K at pressure ratios exceeding 4. The facility was equipped with a 50.8-mm-diam convergent test nozzle attached to a source-section duct. The source section provides the acoustic excitation of the flow. The section consists of eight acoustic drivers, coupled in pairs, equally spaced along the circumference of the nozzle supply duct. Details of the test facility may be found in Refs. 8, 9, 15, and 17.

Mean flow surveys were made using commercial pressure-sensing probes (United Sensor, Validyne).[15,17] The sound pressure levels at the nozzle exit were measured by a 6.4-mm-diam B&K microphone placed in the nozzle exit plane, outside the nozzle, at a distance of 100 mm from the nozzle axis. Since the pressure levels measured by the microphone placed outside the nozzle were not equal to those at the nozzle exit, the corrections were obtained in advance by making simultaneous measurements directly at the nozzle exit center.[15]

The jet-flow facility is equipped with a single-converging-mirror schlieren system in which the light makes a double pass through the test section. The system uses a wedge mirror instead of splitter plate to separate the beams from the source and to the knife edge.

The schlieren system was used for a photographic ensemble averaging of periodic structures in a tone-excited jet. The method of photographic ensemble averaging consists of repeated synchronized triggering of a light source and superposition of all the schlieren images on a single photographic film to reinforce the image of the coherent periodic structure in the flow. The frequency of repeated photographic shots is usually limited to low frequencies by mechanical shutter restrictions or light-source recharging limitations. The schlieren system developed recently at Lockheed is unique in that it enables photographic ensemble averaging of periodic flow structures with frequencies up to the order of 100 kHz.

The system uses monochromatic laser light. The light source consists of a continuously operating 18-W Ar-ion laser, Bragg cell modulator, and spatial filter. In operation,

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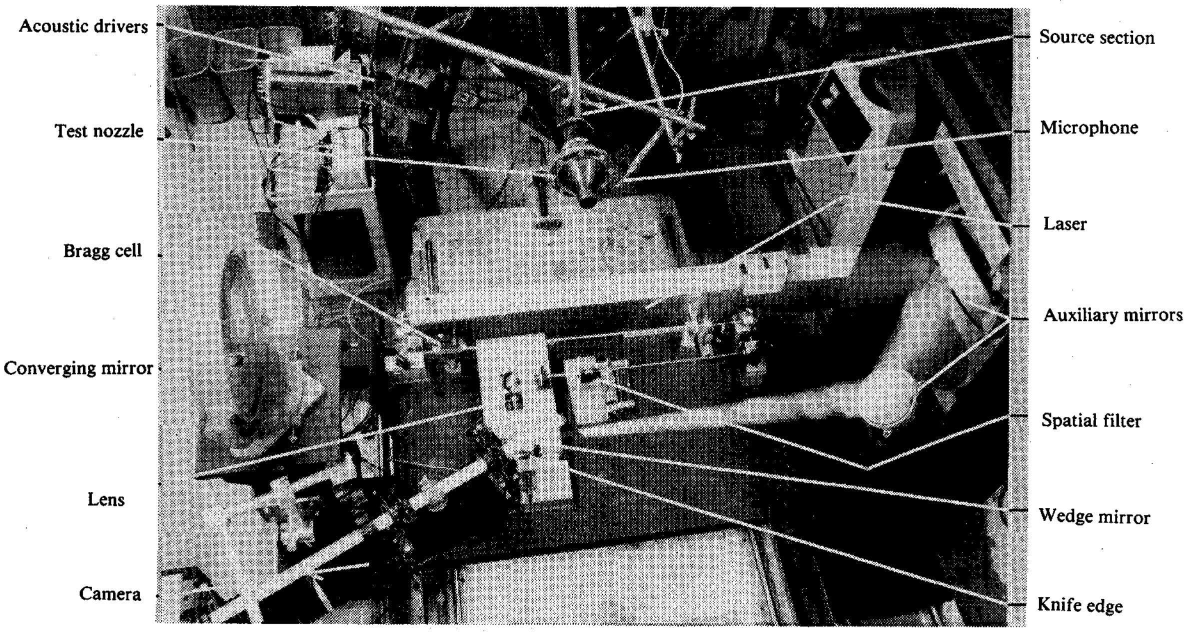

Fig. 1 Free jet test facility.

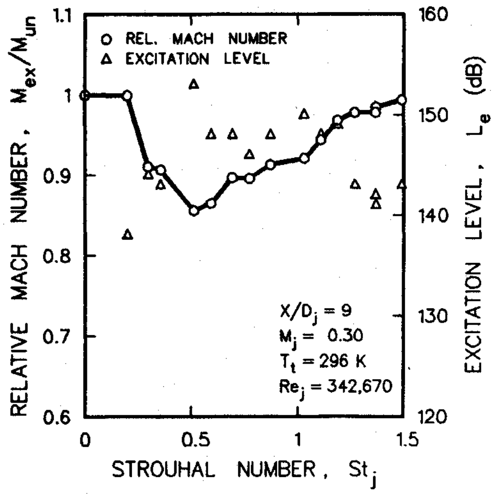

Fig. 2 Excitation Strouhal number effects on a low Mach number, unheated jet.

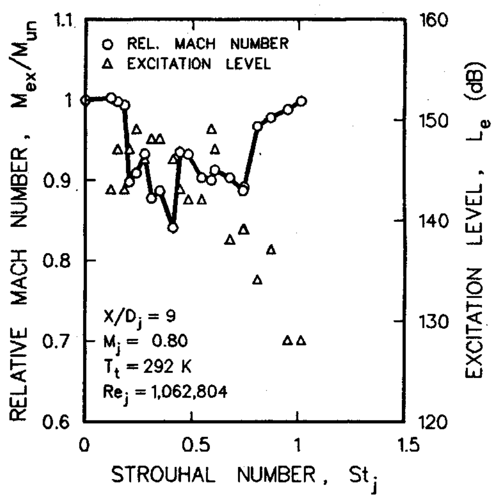

Fig. 3 Excitation Strouhal number effects on a high Mach number, unheated jet.

the excited Bragg cell acts as a shutter, deflecting the laser beam off the spatial filter and thus effectively blocking the laser beam from a photographic plate. Because the Bragg cell is excited by an electronic signal of a frequency in a MHz range, the shutter is no longer limited to low frequencies. A simple electronic device controlling the Bragg cell excitation enables the selection of both the frequency of photographic shot repetition and the time exposure of each of the shots.

Mean Flow Data

Mean flow measurements were made to determine the excitation Strouhal number that produced the greatest changes in the jet flowfield. The experiments consisted of measuring flow parameters on the jet centerline at nine nozzle exit diameters downstream of the nozzle exit for different jet operating and flow excitation conditions. The local Mach number at this point was compared with the Mach number at the same point in the jet flowfield but in the absence of upstream acoustic excitation. The selection of the optimum excitation frequency was based on a variation of this Mach number ratio (excited/unexcited) with the excitation Strouhal number.

The majority of the results were obtained at Mach numbers of 0.3 and 0.8 and temperatures of up to 800 K. The Reynolds numbers, based on the nozzle exit diameter, ranged from 350,000 to 1,300,000. Excitation Strouhal numbers used were in the range of 0.3-0.6. The excitation sound pressure levels were the maximum levels of excitation achievable at the particular Strouhal number.

The experimental results showed that proper upstream tone excitation enhances the mixing of unheated jets for low-speed conditions as well as for high-speed, high Reynolds number conditions. These results are shown in Figs. 2 and 3, where the variation of Mach number ratio is plotted as a function of excitation Strouhal number. As seen in these figures, the most effective excitation Strouhal numbers were in the range of 0.4-0.5. The heated jet, however, showed a response to upstream excitation that depends on jet Mach number. As seen in Fig. 4, the heating of the jet significantly improved its excitability at $M_j = 0.3$ with respect to the unheated case (Fig. 2). However, at a Mach number of 0.8, the heated jet was not so susceptible to upstream excitation, as shown in Fig. 5. In fact, no effect of upstream acoustic excitation on jets heated above a total temperature of 600 K

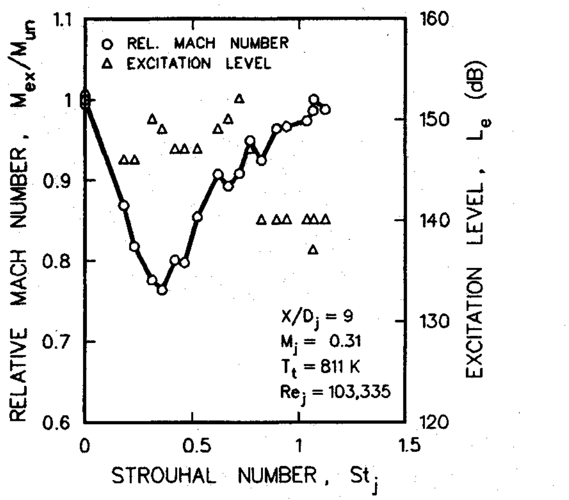

Fig. 4 Excitation Strouhal number effects on a low Mach number, heated jet.

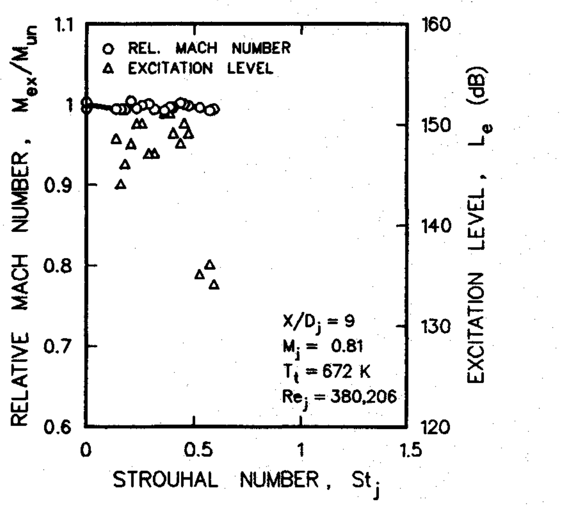

Fig. 5 Excitation Strouhal number effects on a high Mach number, heated jet.

at a Mach number of 0.8 was observed at all for the excitation levels achievable from the present setup.

The effect on jet excitability of increased jet total temperature at jet Mach numbers of 0.3 and 0.8 is summarized in Fig. 6.[17] It is seen in this figure that raising jet total temperature promoted the excitability of the low-speed jet ($M_j = 0.3$), whereas it gradually decreased the excitability of the high-speed jet ($M_j = 0.8$) up to a threshold above which the jet appeared to be totally insensitive to the upstream acoustic excitation. This was true at least for the achievable excitation levels less than 150 dB and Strouhal numbers in the range of 0.35-0.5.

Flow Visualization Experiments

Flow visualization studies of the jet nearfield started with the low-speed jet conditions. For a Mach number of 0.3, however, the sensitivity of the schlieren system was not high enough to make good-contrast pictures. Therefore, the Mach number was raised to increase the density gradients in the flow and in that way to improve the contrast of the schlieren pictures. In order to visualize in detail the development of the large-scale structure, the schlieren pictures were taken with a "corner" knife edge to utilize the effects of both horizontal as well as vertical knife-edge orientation in a single picture. Each of the presented pictures consists of about 20 repeated 5-μs exposures.

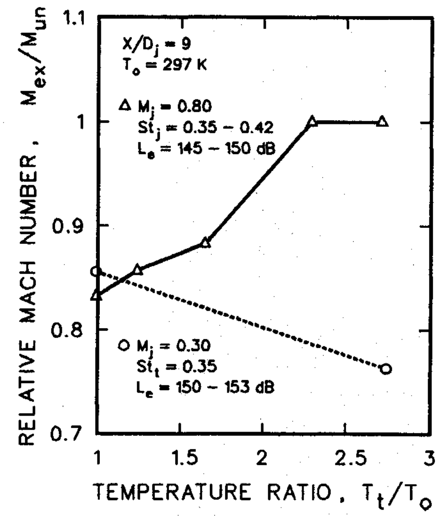

Fig. 6 Jet total temperature effects on acoustically excited jets.

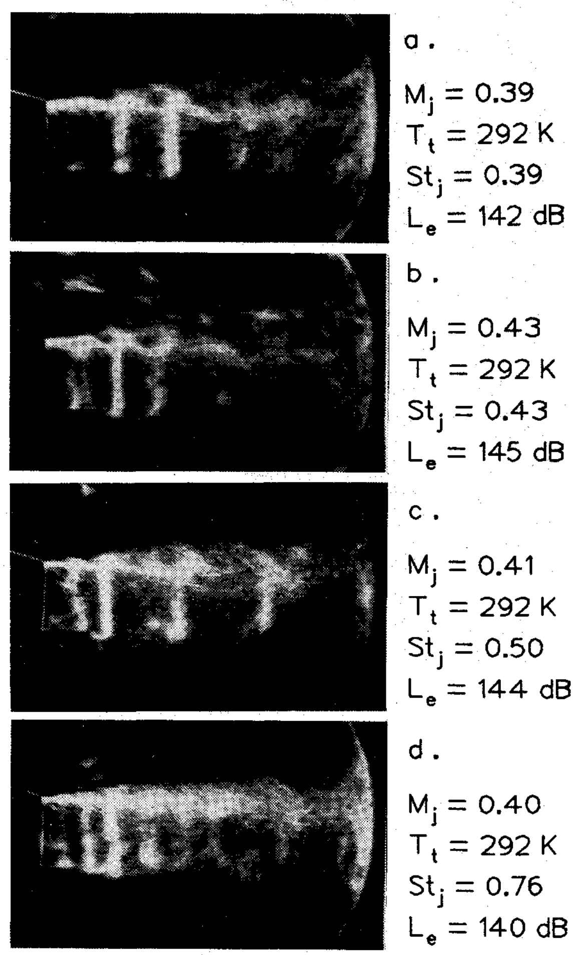

Fig. 7 Ensemble-averaged photographs of tone-excited, unheated, low Mach number jets.

Figure 7 shows the response of the unheated jet to upstream acoustic excitation at a Mach number of ~0.4. As seen in the figure, the vorticity shed from the nozzle lip appears to be in the form of vortex rings. The vortex rings are obviously very stable, keeping their form until they diffuse some five nozzle diameters downstream of the nozzle exit. The essential features of the vortex movement and mutual interaction can be observed in Fig. 8, where a series of pictures with a constant phase shift of 60 deg is shown. Two

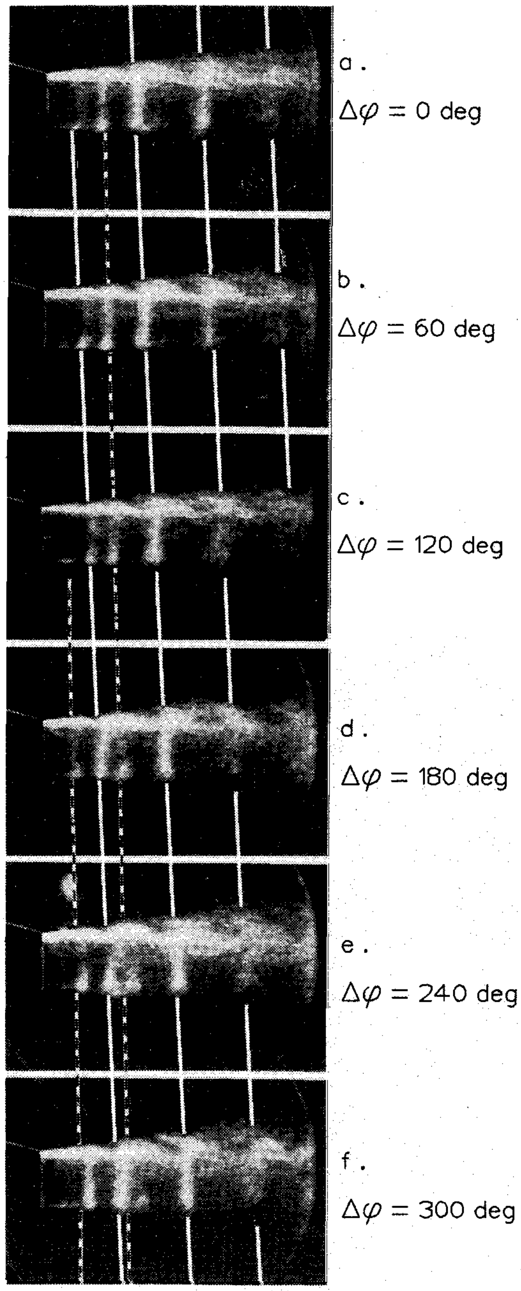

Fig. 8 Phase-locked ensemble-averaged photographs of large-scale structure development in a tone-excited, unheated free jet ($M_j = 0.48$, $T_t = 292$ K, $St_j = 0.61$, $L_e = 145$ dB)

vortex structures are traceable in this series. The main structure, highlighted by solid lines, tended to maintain its formation in the flow and was convected relatively far down the flow with a velocity of $0.67U_j$. The secondary structure, highlighted by broken lines, had a shorter lifetime because it was convected with a lower velocity, $0.45U_j$, and its vortices were overtaken and absorbed by the vortices of the main structure (Fig. 8f). This process is often referred to as a vortex coalescence,[18] or vortex pairing.[6] For the sake of completeness, the picture of the unheated, unexcited jet of $M_j = 0.48$ is shown in Fig. 9.

At high Mach number, a considerable distortion of the vortex structure in a tone-excited jet was observed. As seen in Fig. 10, the vortex rings at this Mach number were no longer perpendicular to the jet axis. Also, it appears that vortices diffused faster than in the low-speed tone-excited jet. The picture of the unexcited, unheated, high-speed jet is shown in Fig. 11.

Fig. 9 Ensemble-averaged photograph of an unexcited, unheated, low Mach number jet ($M_j = 0.48$, $T_t = 292$ K).

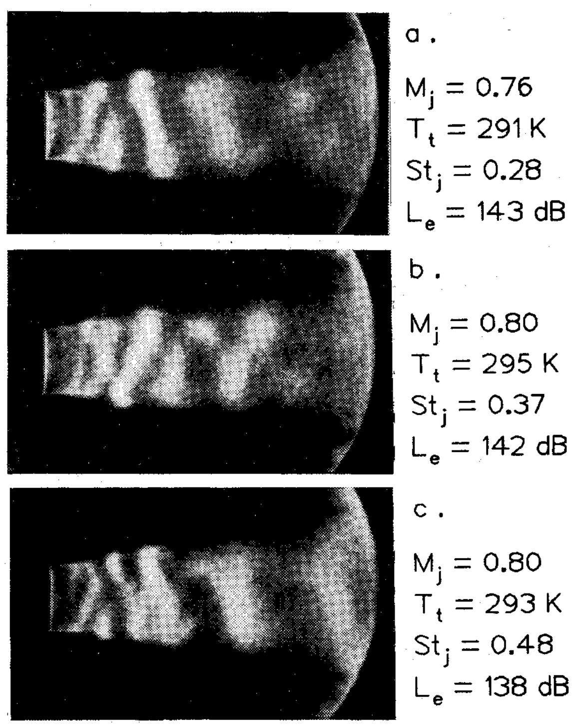

Fig. 10 Ensemble-averaged photographs of tone-exited, unheated, high Mach number jets.

The unexcited low Mach number jet, heated up to a total temperature of 670 K, is shown in Fig. 12. Due to the heating of the flow, the schlieren pictures have much better contrast. As mentioned in the previous section, heating the low Mach number jet significantly improved its excitability. A similar conclusion may be drawn from the flow visualization study. As seen in Fig. 13, there was a well-defined ring-vortex structure in the flowfield of a heated low Mach number jet acoustically excited in the range of Strouhal numbers from 0.25 to 0.45.

The vortex structure in the heated jet appeared to diffuse faster than in the unheated, low-speed, tone-excited one. It diffused at approximately four exit diameters downstream from the nozzle exit plane. At an excitation Strouhal number of 0.25, pairing of two vortex structures was observed. As seen in Fig. 14, two vortex structures were present in the flow. The main one (solid lines) was convected with a velocity of $0.35U_j$. The secondary structure (broken lines) was convected with a higher velocity of 0.5 U_j; its vortices thus caught up and fused with the vortices of the main structure. At the higher-excitation Strouhal number of 0.45, no vortex pairing was observed. As seen in Fig. 15, vortices were convected with a velocity of $0.3U_j$ and kept a constant distance from each other. Similar behavior of the vortex structure of a jet excited at high Strouhal numbers ($St_j > 1.2$) is reported in Ref. 18.

At a high Mach number of 0.8, the jet heated to $T_t \sim 670$ K did not respond to upstream excitation at the maximum allowable level of 136 dB. As seen in Figs. 16 and 17, there was no visible difference between the tone-excited and unexcited jets at the given jet operating and tone-excitation conditions. This observation agrees with the conclusion drawn from the results of mean flow experiments. Perhaps much higher levels are needed to excite high Mach number heated jets. Further work to excite such jets is currently being continued at the Lockheed-Georgia Company.

Comparison with Theoretical Predictions

The experimental results are compared with theoretical predictions based on the analysis of Tam and Morris. The formulation of the analysis is contained in Refs. 8 and 15. The prediction scheme consists of two parts. In the first, the coupling between the upstream acoustic excitation and the instability waves of the jet is calculated. In the second, the interaction between the instability wave and the jet flowfield is determined using a quasilinear integral analysis. The schemes enables predictions to be made of the absolute levels of the excited instability waves, as well as of the time-averaged properties of the turbulent jet.

The agreement between the predictions and the experiments is very good for the high- and low-speed unheated or moderately heated jet conditions. Figure 18 shows such comparison for jet operating conditions of $M_j = 0.48$ and $T_t = 488$ K. For highly heated jets, however, the theoretical results continue to indicate a response of the jet to upstream acoustic excitation contrary to the experimental results. Further work is necessary to verify the theory for highly heated, harmonically excited jets.

Discussion

The results presented above suggest that for the test conditions used in this study, high Mach number heated jets are considerably less excitable than similarly heated low Mach number jets. Possible reasons for that finding are discussed below.

Excitation Levels

The excitation levels at the nozzle exit plane were measured directly only for the unheated jets. For the heated jets, however, the excitation level was determined indirectly by a microphone placed outside the nozzle but in the plane of the jet exit. The necessary corrections between the inside and the outside microphones were obtained in advance by making simultaneous measurements of the sound levels present at the nozzle exit for each excitation frequency. These calibrations were made for unheated conditions only, and it was assumed that the corrections were also valid for heated conditions. No direct excitation level measurements were performed for the heated jets, so the actual excitation levels for these conditions may be questioned.

Harmonic Content of the Excitation Tone

In most of the results presented here, whenever high levels of acoustic excitation were generated at the frequency of interest, additional noise was generated at the harmonics of the fundamental. The effect that the presence of these harmonics had on the jet flow structure is not known at present.

Excitation Mode

During the experiments, the acoustic drivers were operated in the axisymmetric mode. The actual excitation mode at the nozzle exit plane exhibited a certain degree of distortion at various frequencies; however, the axisymmetric plane wave mode was always dominant. The low-speed unheated and heated jets responded to this excitation with axisymmetric large-scale structures (Figs. 7, 8, 13-15). However, as seen in Fig. 10, the unheated high Mach number jet produced an

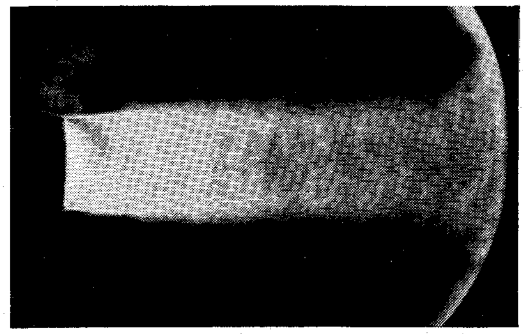

Fig. 11 Ensemble-averaged photograph of an unexcited, unheated, high Mach number jet ($M_j = 0.8$, $T_t = 291$ K).

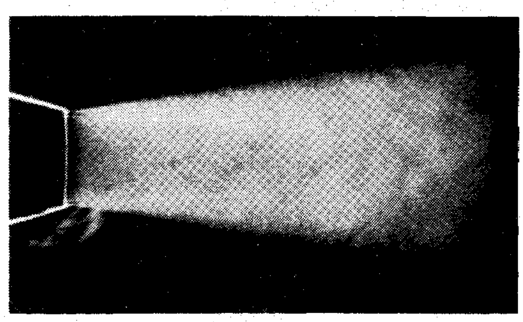

Fig. 12 Ensemble-averaged photograph of an unexcited, heated, low Mach number jet ($M_j = 0.3$, $T_t = 666$ K).

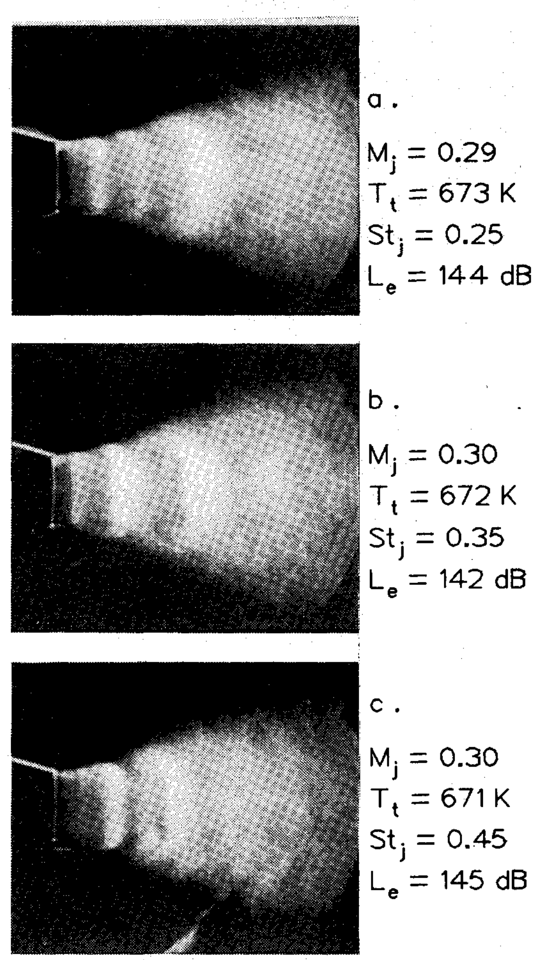

Fig. 13 Ensemble-averaged photographs of tone-excited, heated, low Mach number jets.

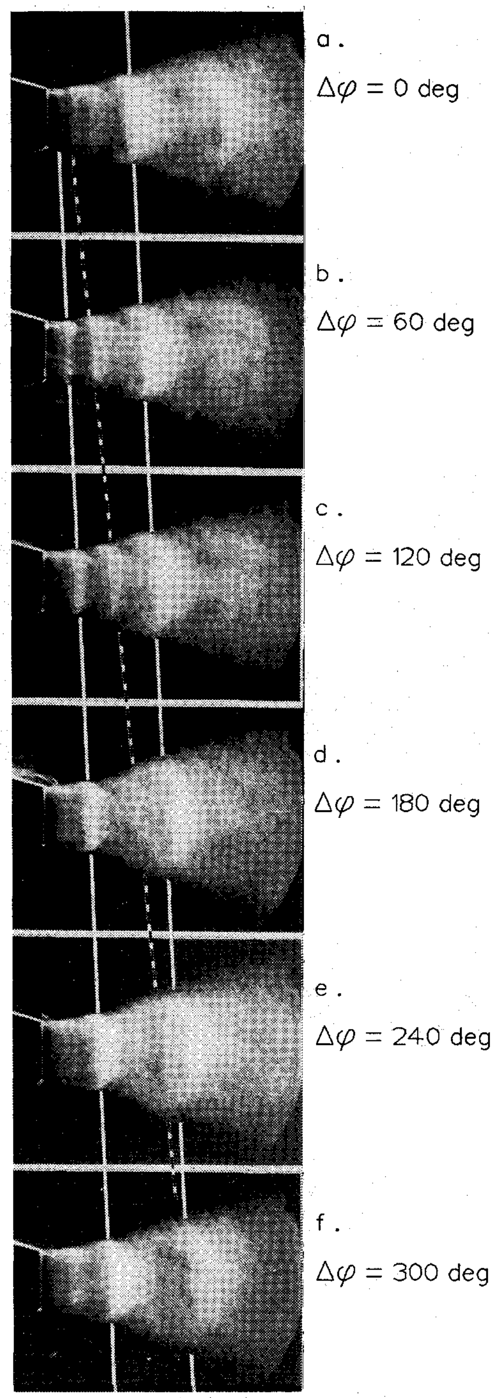

Fig. 14 Phase-locked ensemble-averaged photographs of large-scale structure development in a tone-excited, heated free jet ($M_j = 0.29$, $T_t = 673$ K, $St_j = 0.25$, $L_e = 144$ dB).

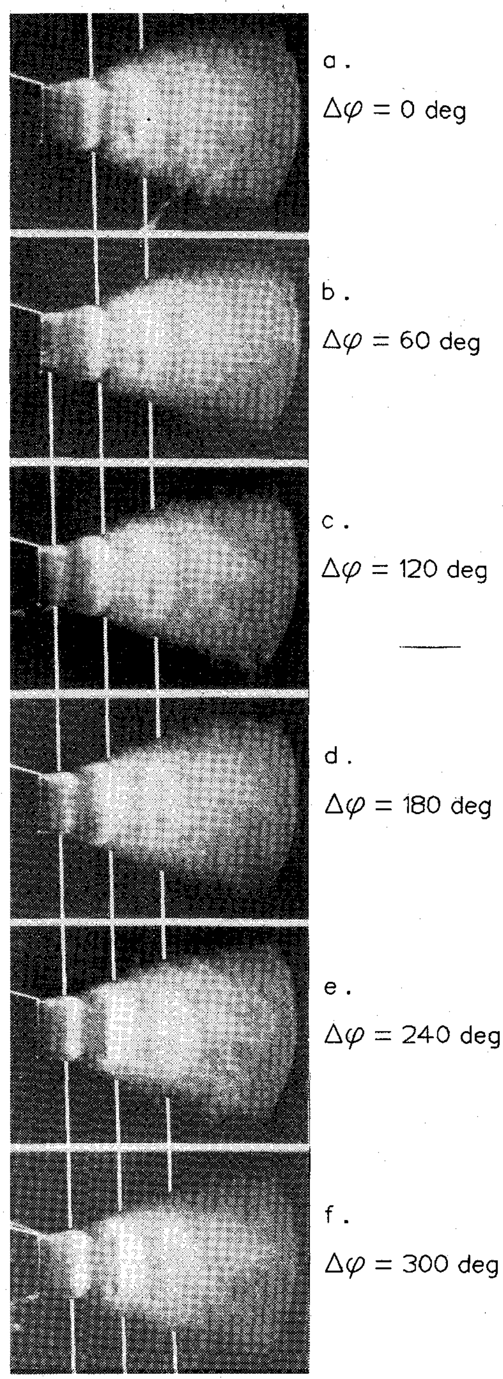

Fig. 15 Phase-locked ensemble-averaged photographs of large-scale structure development in a tone-excited, heated free jet ($M_j = 0.30$, $T_t = 672$ K, $St_j = 0.45$, $L_e = 145$ dB).

asymmetrically organized large-scale structure in response to this excitation. Thus, it may be possible that the actually existent mode of excitation at the nozzle exit plane was not the most effective mode of excitation for high-speed highly heated jets.

Turbulence Intensity Level

Turbulence intensity level at the nozzle exit plane was not measured in the present study. However, previous measurements in the same test facility showed that the turbulence intensity at the nozzle exit plane increases due to the heating of the flow. For example, the turbulence intensity of the unheated jet of $M_j = 0.78$ was 0.8% while the same jet heated to $T_t = 800$ K had a turbulence of 2%. The increased turbulence intensity increases natural mixing and thus lessens

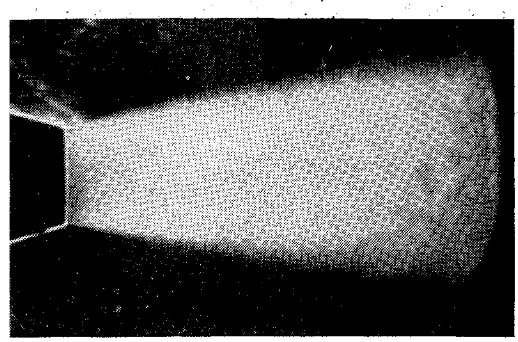

Fig. 16 ensemble-averaged photograph of an unexcited, heated, high Mach number jet ($M_j = 0.80$, $T_t = 663$ K).

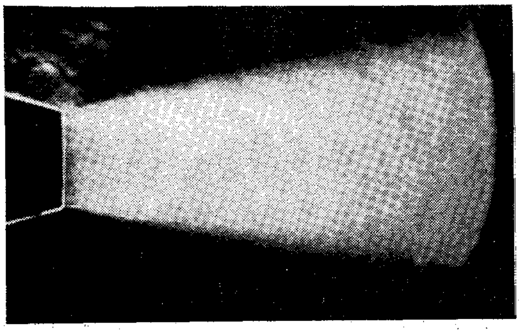

Fig. 17 Ensemble-averaged photographed of a tone-excited, heated, high Mach number jet ($M_j = 0.80$, $T_t = 674$ K, $St_j = 0.32$, $L_e = 136$ dB).

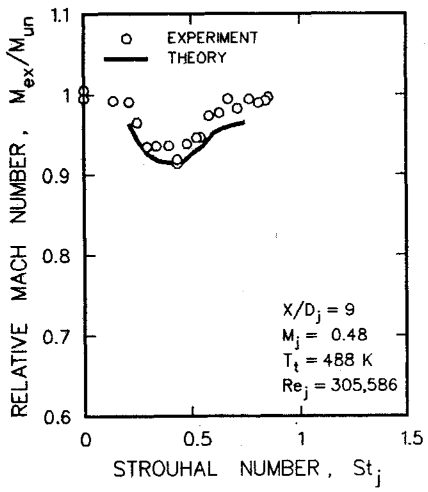

Fig. 18 Comparison between theory and experiment.

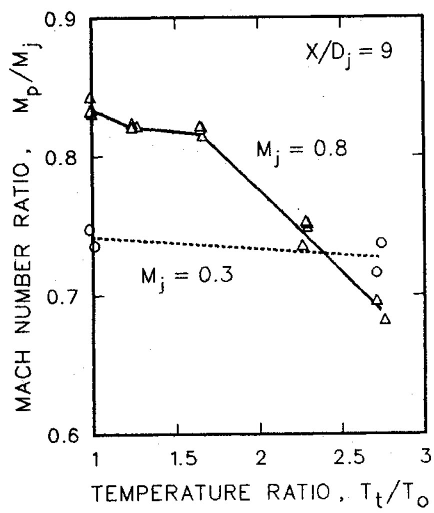

Fig. 19 Total temperature effects on centerline local Mach number at $X/D = 9$ of unexcited jets.

the effective potential for mixing enhancement by artificial excitation.

Natural Mixing of Heated Jets

Experiments with unexcited heated jets revealed that the effects of heating are different for low- and high-speed jets. As seen in Fig. 19, at high Mach number the effect of heating the jet was to provide noticeable decrease of the centerline local Mach number at $X/D = 9$, thus indicating considerable broadening of the jet plume. For the $M_j = 0.3$ jet, however, no such broadening was observed. It is these results that may be the crux of the matter in terms explaining why the imposed excitation had little effect on the $M_j = 0.8$ jet. This jet has probably achieved sufficient natural excitation due to the heating, so that any further excitation probably would require a considerably higher excitation level.

Conclusions

The main findings of this investigation of the acoustic control of free jet mixing are summarized as follows:

1) The sensitivity of free jets to acoustic excitation varied strongly with the jet operating conditions.

2) A coherent periodic structure in the form of ring vortices was formed in the near flowfield of an acoustically excited free jet. The structure was very stable with well-defined ring vortices at low Mach numbers. Certain distortion of this structure was observed for a high Mach number unheated jet.

3) Vortex pairing was observed on schlieren pictures at some of the excitation conditions at low Mach numbers. At high Mach numbers, no mutual vortex interaction was traceable.

4) Good qualitative agreement was achieved between the results of the mean flow measurements and the flow visualizations.

5) Good agreement between the predictions and the experiments was limited to unheated or moderately heated jet operating conditions.

Acknowledgments

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