Amplification of Jet Noise by a Higher-Mode Acoustical Excitation

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As shown in previous experiments, the broadband sound radiation of a turbulent jet can be amplified by a pure-tone sound excitation. This interaction takes place at perturbation levels lower than those found in aircraft engines. The previous experiments, however, have been carried out only with sound excitation of plane sound waves coming from inside the nozzle. In contrast to that, the present investigation shows that broadband jet noise amplification can be produced even by an acoustical excitation at higher modes. At exciting frequencies below the cut-on frequency of the nozzle exit cross section, the exciting tone is masked by the amplified jet noise in the radiated far field.

Introduction

USUALLY, the noise radiation from aircraft engines is assumed to consist of several independent contributions. These contributions can have a periodic character as, e.g., the tones produced by rotating machinery, or they can possess a more stochastic structure as, e.g., the jet noise. It is not obvious that a pure-tone excitation can amplify the broadband noise emission of a turbulent jet. However, it has been shown by model experiments with a cold jet that such an effect can take place at perturbation levels and at Mach numbers that are likely to be met in real aircraft engines.[1] This effect has been confirmed by the independent investigations of Moore.[2] The aforementioned experiments were carried out with a plane wave acoustic excitation from inside a circular nozzle. In this case, a typical amplification rate of the broadband jet noise of 6-7 dB can be produced by a sinusoidal velocity perturbation level of about ½% at the nozzle exit (Mach number $M=0.6$, Strouhal number $S_D=0.5$). Nevertheless, at those conditions, the tonal component dominates the far-field radiation. Its filtered sound pressure level exceeds the mere (amplified) broadband jet noise content by 5-9 dB.

An excitation of the jet by both plane sound waves (e.g., combustion noise) and sound waves at higher modes (e.g., turbine tones) can be regarded as a typical situation in aircraft engines. Therefore, the present investigation is extended to higher modes of sound excitation. It will be shown that in this case the exciting pure tone can be masked by the amplified jet noise in the far-field radiation.

Experimental Appartus

Figure 1 shows the test facility in the anechoic chamber. The compressed air supply for the test facilitiy consists of a high-speed radial compressor with electronic shaft speed control (not shown in Fig. 1). The air is passed through a muffler to suppress noise from the compressor and from valves and bends in the air supply line. A nonreflective termination is connected to the muffler, which consists essentially of a tube with a slot of varying cross section covered with felt (designed according to Shenoda[3]). The slotted tube is mounted in a vessel so that no pressure difference can exist between inside and outside the slot. The interior walls of the vessel are covered with acoustic lining material. Sound is produced by four piston-loudspeakers, each with 60 W electric power input.

The most interesting effects should occur with acoustical excitation at higher modes below the cut-on frequency of each of these modes. Consequently, the acoustical excitation should not be introduced too far from the nozzle exit in order to avoid too low a level of the (rapidly decaying) fluctuating velocities in the nozzle exit section. The loudspeaker arrangement used for the generation of higher modes can be seen in Fig. 2. The loudspeakers are connected by resonance tubes to the nozzle tailpipe. The lateral holes in the tailpipe are covered by a fine-meshed grid to avoid the generation of edgetones.

Unfortunately, the determination of a reference quantity [like the axial fluctuation velocity in the plane wave (mode 10) case] is not as easy to obtain for higher modes. An adequate quantity for the first higher mode (mode 1, "fish-tail" motion of the jet) would be the radial fluctuating velocity on the axis in the nozzle exit plane. Because this velocity is of the order of 1/10% of the mean velocity, calibration problems in hot-wire anemometry (at those Mach numbers) seem to exclude a direct measurement by X-wire probes. The authors feel that in the present stage of the investigation the statement of phenomena is most essential. It should be sufficient, therefore, to measure a reference pressure at a certain location to ascertain the reproducibility of the experiments. The reference pressure is taken in the nozzle exit plane on the axis by a 1/8-in. Brüel and Kjaer microphone with nose cone. For this reference pressure measurement, only one of the four loudspeakers was switched on. In contrast to this, all four loudspeakers were switched on during the experiments, the magnitude and phases being adjusted by the microphone in the plexiglas duct on the axis.

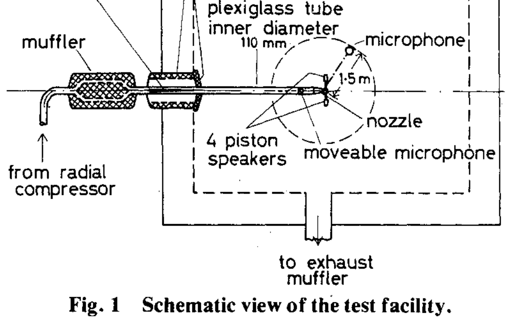

Fig. 1 Schematic view of the test facility.

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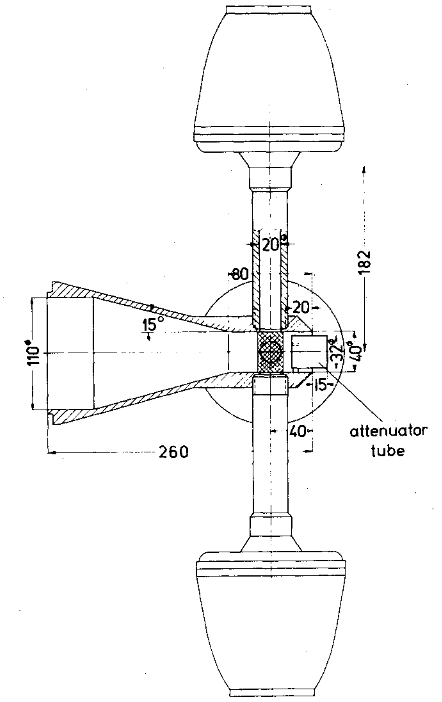

Fig. 2 Nozzle with loudspeakers for the generation of higher acoustical modes. The attenuator tube is used only in the experiments shown in Fig. 6.

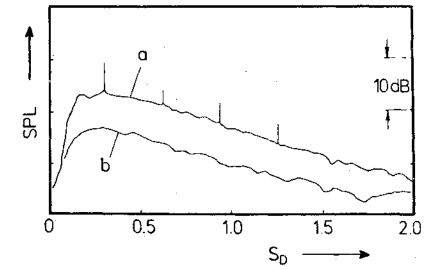

Fig. 3 Frequency (Strouhal number) spectra of the far-field sound pressure at 45° from the axis (mode 1 excitation). Nozzle configuration: see Fig. 2. Curve a: with sound excitation at a Strouhal number $S_D = 0.3$, reference sound pressure level 139.4 dB. Curve b: without excitation.

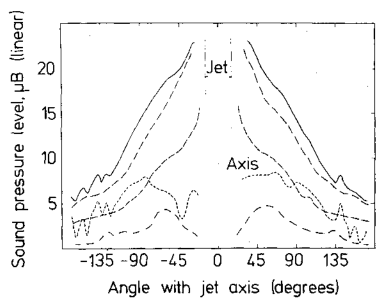

Fig. 4 Angular distribution of the different sound pressure contributions in the far field (mode 1 excitation) without attenuator. Nozzle configuration: see Fig. 2. Strouhal number and reference sound pressure level equal to the values in Fig. 3 (——, overall sound pressure; —·—, broadband noise contents with excitation; ———, broadband noise without excitation; ---, contents of the basic wave component of the sound excitation; —····—, contents of the first harmonic of the sound excitation).

During the "mode 1" excitation, two opposite loudspeakers were adjusted in equal magnitude and opposite phase (180° phase shift). The quality of this adjustment was checked by a movable microphone on the air supply tube axis (see Fig. 1). At 180° phase shift, zero sound pressure should be measured on the tube axis. The two loudspeakers in the perpendicular position (relative to the first pair) were adjusted in the same way, but the phase of these latter two loudspeakers was shifted by a 90° phase delay relative to the first pair of loudspeakers. In this way, a spinning acoustical excitation generating a screwlike jet deformation could be produced. The effects in the jet flowfield and in the acoustical far field should be, therefore, nearly axisymmetric. The "mode 2" (elliptic) deformation of the jet can be produced by an opposite sign of the sound excitation of each neighboring pair of loudspeakers of the system. By using four loudspeakers, only standing acoustical waves, in the circumferential direction, can be generated. Thus, no perfect axial symmetry in the jet deformation can be achieved. The present "mode 2" far-field measurements have been taken in the horizontal plane, in which both the jet axis and one pair of loudspeakers are located.

The radiated far field is measured by a ½-in. Brüel and Kjaer condenser microphone with nose cone mounted on a beam that can be rotated around the center point of the nozzle end section. The distance is 75 times the radius at the nozzle exit. Pure-tone sound and broadband noise of the radiated sound field were separated by Brüel and Kjaer narrow-band slave filters. For the isolated measurement of the basic component of the pure-tone excitation, one narrow-band filter was used. In contrast to that, for the isolated measurement of the broadband noise emission, two narrow-band slave filters in "rejection" position were used in order to suppress the basic component and the first harmonic of the exciting sound. Careful testing showed that the higher harmonics had negligible magnitude compared to the magnitude of the broadband noise.

Experiments with Higher-Mode Acoustic Excitation

The present experiments are restricted to a relatively low Strouhal number ($S_D = 0.3$, $M = 0.6$), the frequency being far below the cut-on frequency of the cylindrical part of the nozzle tailpipe. Within this frequency region, the far-field pure-tone sound radiation should be a minimum due to the nearly perfect cancellation of the radiation of the loudspeakers. On the other hand, velocity fluctuations suitable for perturbation of the jet should occur near the nozzle. In Fig. 3, the spectral distribution of the radiated sound with and without pure-tone excitation can be seen.

As in the plane wave excitation,[1] we obtain a broadband noise amplification. In the example of Fig. 3, this amplification is about 6 dB. Because of the small radiation efficiency of a higher-mode acoustical wave below the cut-on frequency, one obtains a comparatively weak pure-tone radiation in the far field.† The authors carried out additional experiments at slightly lower excitation levels in which it already is difficult to identify the pure-tone excitation in the far-field spectrum. In this latter case, however, the broadband jet noise amplification is still, say, 4 dB. The angular distribution of the radiated sound can be seen in Fig. 4. All data are the same as in Fig. 3. It is evident that the far-field radiation now is dominated by the amplified broadband jet noise. The basic sine wave component of the acoustic excitation is far below the total noise output. Thus, it is evident that near-field fluctuations at the nozzle exit can exist but hardly contribute by themselves to the noise output of the system. They are, however, able to amplify the total noise output via jet noise amplification.

Because of nonlinear effects in the loudspeakers, even the first harmonic of the excitation is detectable in these far-field

†If one changes the phase relation of the loudspeakers at constant electric power input so that a plane acoustical wave is generated instead of a spiral wave, one obtains 1) nearly the same broadband jet noise amplification, 2) a dramatically increased pure-tone far-field radiation, which, e.g., yields about a 30 dB higher sound pressure level of the basic tone contents at an angle of 45° with the jet axis.

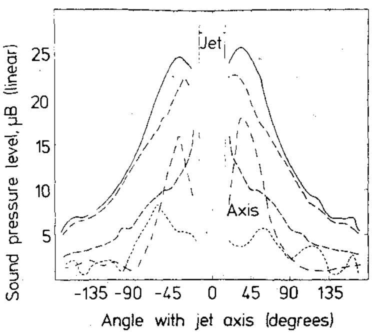

Fig. 5 Angular distribution of the different sound pressure contributions in the far field (mode 2 excitation) without attenuator. Strouhal number and reference sound pressure level equal to the values in Fig. 3 (——, overall sound pressure; —·—, broadband noise contents with excitation; ———, broadband noise without excitation; ---, contents of the basic wave component of the sound excitation; —···—, contents of the first harmonic of the sound excitation).

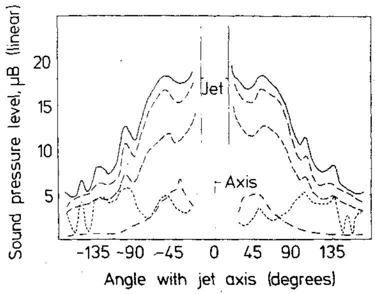

Fig. 6 Angular distribution of the different sound pressure contributions in the far field (mode 1 excitation) with attenuator. Strouhal number and loudspeaker power input equal to the values in Fig. 4 (——, overalll sound pressure; —·—, broadband noise contents with excitation; ———, broadband noise without excitation; ---, contents of the basic wave component of the sound excitation; —···—, contents of the first harmonic of the sound excitation).

measurements. This component is not canceled by the interaction of the four loudspeakers. Higher harmonics have been found to be irrelevant. To prevent misinterpretations, it should be stressed that the contents of higher harmonics in the far field are caused mainly by mechanical nonlinearities in the loudspeaker systems. In addition, the angular distribution of the basic wave component in Figs. 4-6 is highly sensitive to very small geometrical asymmetries and to only slight inaccuracies in the magnitude and phase adjustment of the loudspeakers. Therefore, the angular distribution of the basic wave component should give an impression of the low magnitude of the exciting wave in the far field rather than being a precise measurement of this component. This restriction is not valid for the other components of the far-field radiation measurement which are considered to be measured precisely.

Experiments with a "mode 2" acoustic excitation (elliptic deformation of the jet) show results similar to those just obtained (see Fig. 5). Here, however, the first harmonic of the pure tone is more dominant in the far field than the basic wave component. Again, the higher harmonics are irrelevant. It is evident that broadband jet noise amplification also can be produced by a "mode 2" excitation of the jet.

Suppression of the Jet Noise Amplification

Unfortunately, there is no detailed information available on the turbulence structure of the acoustically excited fully turbulent jet. We assume that the wave motion of the jet column is analogous to that observed by Crow and Champagne[4] and that there is some change in the turbulence of the wavelike deformed jet which causes an increased broadband sound radiation. Thus, we concentrate our effort on the attenuation of the generation of the acoustically excited boundary-layer waves. To achieve this, we use a simplified plane model consisting of a semi-infinite plate from which a shear layer is shed which separates a region of constant flow and a region of a medium at rest. The interaction of a fluctuating forcing motion with such a simplified flow model has been studied recently by Crighton and Leppington[5] and by Bechert and Michel.[6] For an incompressible flow, Bechert and Michel obtained a general solution for the motion of the free shear layer excited by an arbitrary exterior pulsating flow:

$$v_0=\frac{\omega}{\bar{u}}Re\left\{e^{-i\omega t}\left[e^{\lambda_2 x}\int_0^x e^{-\lambda_2 x}\cdot v_{0q}(x)\,\mathrm{d}x - e^{\lambda_1 x}\int_0^x e^{-\lambda_1 x}\cdot v_{0q}(x)\,\mathrm{d}x\right]\right\} \tag{1}$$

with

$$\lambda_1 (\omega/\bar{u})\cdot(i+1),\quad \lambda_2=(\omega/\bar{u})\cdot(i-1) \tag{2}$$

In this equation, v_0 is the vertical velocity component (normal to the shear layer) of the fluctuating flow at the shear layer on the side of the medium at rest, $\bar{u}$ is the mean flow velocity in the x direction, ω is the angular frequency of the fluctuating forcing flow, and v_{0q} is the v-velocity component that would be generated if the mean flow were absent. The boundary layer can be excited by both potential flow fluctuations (i.e., sound) and/or fluctuations induced by convected vorticity.

From the general solution (1), we can extract a qualitative understanding of the manner in which the boundary-layer control takes place even in more complex cases such as, e.g., a pulsating nozzle flow at finite subsonic Mach numbers. A trivial but effective method is, of course, the reduction of the magnitude of the fluctuations by acoustic lining of the nozzle or tailpipe. Another effective method is, at a given $\int_0^\infty v_{0q(x)}\,\mathrm{d}x$ (incompressible assumption of constant volume flux across the shear layer), to "smear" the v_{oq} distribution in a streamwise direction to reduce the value of the integrals in Eq. (1). This means that peaks of v_{oq} such as that near the trailing edge of the nozzle should be reduced. This "smearing" can be achieved by the following methods: 1) introduction of a plate (or tube) near the nozzle edge to reduce the local v_{oq} magnitudes; or 2) generation of a continuous transition from "existence of the wall" to "absence of the wall" by a slotted or porous construction of the tailpipe over a length of about one nozzle diameter; obviously, this approach is related closely to the attenuation by acoustic lining of the tailpipe.

Method 1 has been tested successfully with a plane wave excitation.[1] Experiments with the attenuator tube were carried out even with a "mode 1" acoustic excitation, the tube configuration being shown in Fig. 2. The results of the directivity measurement in the far field can be seen in Fig. 6. The acoustic excitation and the flow properties were kept constant with reference to Fig. 4.‡

The insertion of the attenuator causes the following changes:

1) Without acoustical excitation, there is an irrelevant change in the directivity pattern of the pure jet noise (compare Figs. 4 and 6); an amplification (no attenuation) of this pure jet noise by about 0.5 dB can be observed.

‡Because of the change in the nozzle end configuration, the sound pressure level of the excitation field at the nozzle end is increased by 2.8 dB in comparison to Fig. 4. For these reference pressure measurements, only one loudspeaker was switched on, and the loudspeaker voltage was constant in both cases, without and with attenuator tube. However, this change in the nozzle end impedance is assumed not to change the fluctuating flow between the opposite lateral holes in the nozzle tailpipe to which the loudspeakers are connected. This fluctuating flow should be considered as an adequate reference quantity for the wave excitation of the jet column.

2) With sound excitation, the overall sound pressure level is reduced mostly in the direction of maximum sound radiation (compare again Figs. 4 and 6). In this direction (about 35° from the jet axis), the reduction of the total noise output is about 2 dB, the broadband noise reduction being about 3 dB at this angle and under the given perturbation levels.

It should not be concealed, however, that even the change in the mean flow profile caused by the insertion of the tube can effect the sensitivity of the jet to acoustical excitation. This influence is considered to become essential in particular at high Strouhal numbers.

The aerodynamic drag of the attenuator tube is estimated in the present experimental situation to be 1.5% of the total thrust. This estimation is based on a computation of the friction drag of a flat plate with a fully developed turbulent boundary layer (see e.g., Ref. 7). Since the attenuator device has not been optimized yet, there is some hope that higher noise reductions can be achieved at relatively low thrust losses. Nevertheless, it is clear that the noise reduction potential of these attenuator systems is limited by the coefficient of the jet noise amplification, i.e., on the order of 4-8 dB.

Conclusions

It has been shown that, above a certain excitation level, broadband jet noise can be amplified considerably by a pure-tone excitation. However, for a plane wave excitation (at levels suitable for the jet noise amplification), the pure-tone excitation exceeds the amplified broadband jet noise by, say, 5-9 dB. In contrast to that, the present experiments at higher modes of the acoustic excitation (and in a frequency region below the cut-on frequency of the nozzle end section) show quite different results. Now, the pure-tone acoustic excitation necessary for a 6-dB amplification of the broadband jet noise is masked by the amplified jet noise in the radiated far field.

The velocity fluctuations generated by an acoustic near field of the higher-mode type (and below the cut-on frequency of this mode) do not differ very much from other fluctuations generated, e.g., by turbulence. A theoretical study[6] of the artifical excitation of a free shear layer has shown that there is, in principle, no difference between an excitation by sound or by convected vorticity. Preliminary experiments by the authors[1] confirm that even a jet noise amplification due to the turbulence exists. "Excess noise" is, therefore, also likely to consist of a contribution from jet noise amplification, in addition to the sound generated inside the nozzle or tailpipe. For the pure-tone acoustic excitation of the turbulent jet, it has been shown that the broadband noise amplification can be reduced substantially by inserting a simple tube attenuator into the nozzle exit.

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