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Separation of Core Noise and Jet Noise

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A method of identification and measurement of core noise and jet noise separately has been developed based on cross-correlation of signals from microphones located at widely separated angles in the far field of a jet. The different coherent properties of core noise and jet noise are used in this method to achieve this separation. Experimental data obtained in a small scale facility are analyzed to demonstrate that this method can be used successfully to separate the mean-square pressures of core noise and jet noise.

Nomenclature

A	= autocorrelation function
C	= cross-correlation function or Doppler factor in Eq. (3)
M	= Mach number
N	= index in Eq. (10)
p	= sound pressure
q	= source fluctuation, Eq. (10)
r	= radius
S	= spectral density
t	= time
t'	= retarded time
U, V	= velocity
W	= speed of tape recording
α	= ratio defined in Eq. (4)
β	= ratio defined in Eq. (5)
δ	= density exponent
Δ	= difference
θ	= angle with respect to the downstream jet axis
ϕ	= angle to the direction of motion (Fig. 13)
ρ	= density
τ	= time delay
ψ	= autocorrelation of moving source
ω	= ciruclar frequency

Subscripts and Superscripts

a	= airplane
C	= core
c	= convection
e	= at emission
j, J	= jet
0	= at observation, also ambient
rel	= relative
V_j	= at jet velocity
$1,2$	= angular positions
$(\ )'$	= time derivative

Introduction

A METHOD of evaluating core noise and jet noise separately would be very helpful in clarifying some of the controversial issues in aeroacoustics. An example is the determination of the effect of forward motion of an aircraft on jet noise, because internally generated noise propagated through the jet and jet noise are affected quite differently by forward motion. Cross-correlation of directly measured internally generated sound with the sound pressure measured in the far field can be used as a detection scheme for core noise, but the method is hampered by experimental and interpretational difficulties.[1-3] A simple method of separating the far-field noise into its jet noise and core noise components involving only conventional far-field measurements has been developed.

Description of Method

Sources of core noise are nearly at rest with respect to the engine and, when the noise is perceived, the observer is also generally at rest. This situation prevails for static engine tests and for flight simulation in free-jet wind tunnels which are commonly used in laboratory facilities. Therefore, frequencies of the radiated core noise are preserved unchanged. However, for jet noise whose sources are in motion, the source frequencies undergo large Doppler shifts as the noise is radiated to the far field. As a consquence, the radiated field of jet noise has negligible coherence over widely separated directions, in contrast to core noise which is coherent over all directions. Therefore, the cross-correlation between sound pressures from two microphones separated by a wide angle would essentially represent the autocorrelation of core noise radiated to the far field.

A brief explanation of the behavior of the two-point cross-correlation of jet noise follows. The Doppler shift of the frequency of a source radiating a pure tone is enough to destroy the correlation at two different angles, however small their angular separation. This is true because the long-time average of sound pressure signals of differing frequencies is zero. Jet noise, however, is produced by moving wideband sources which grow and decay. The analysis of the cross-correlation of sound pressures of jet noise sources is conducted more easily in the time domain. Such an analysis together with a comparison of the theory with experimental results is given in Ref. 4. There it is shown that the cross-correlation between two sound pressures at different locations in the radiated field is given by a time integral of a source autocorrelation representing a nonstationary process. The source autocorrelation is a function of a time and a time delay, and is represented by $\psi(t,\tau)$. An example of the source function ψ is given in Ref. 5. The time integral is an integration of ψ over a certain path in the (t,τ) plane. The path of the integration depends upon the positions of the microphones. When the two microphones are at the same location, the paths are parallel to the t axis and produce a large cross-correlation (which is an autocorrelation in this case). However, when the angular separation between

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microphones is increased, the paths slant more and more toward the τ axis, thereby producing a cross-correlation of small value. The limiting value of the cross-correlation is proportional to the τ scale when the paths are parallel to the τ axis, in contrast to the autocorrelations which are proportional to the much larger t scale of the source function $\psi(t,\tau)$. The t scale is approximately 10 times the τ scale in the experimental data shown in Ref. 5 for a jet whose sources convected at a low subsonic velocity equal to 125 m/s.

Another useful observation pertains to the symmetry of the correlation functions about the position of zero time delay. The cross-correlation between two sound pressures from microphones at the same radial distance from the nozzle exit but at different angles is not symmetric about $\tau=0$ because the source of jet noise is not at rest at the nozzle exit. As the data of Ref. 4 show, it tends to be almost antisymmetric about $\tau=0$. Therefore, symmetrization of the observed correlation function tends to reduce its magnitude further. When both jet noise and core noise are present, the operation of symmetry leaves the core noise unchanged but reduces the contribution of jet noise. In any case, the operation of symmetry is mandatory because the cross-correlation between widely separated microphones is interpreted as a core noise autocorrelation function which must be symmetric about $\tau=0$.

Two autocorrelation functions of sound pressures at the angles θ_1 and θ_2 with respect to the jet axis and the cross-correlation between the two sound pressures are determined. Typical curves are indicated in Fig. 1.

The equations needed for separating the mean-square sound pressures of jet noise and core noise are described below. Let $A(\theta,\tau)$ represent the autocorrelation function of sound pressure at the angle θ, at a time delay τ. The value of A at $\tau=0$ gives the mean-square pressure. If A_J and A_C represent the contributions of jet noise and core noise to the observed total autocorrelation A, uncorrelated addition of the two gives the equation

$$A(\theta_1,0)=A_J(\theta_1,0)+A_C(\theta_1,0) \qquad (1)$$

at the angle θ_1, and

$$A(\theta_2,0)=A_J(\theta_2,0)+A_C(\theta_2,0) \qquad (2)$$

at the angle θ_2. Jet noise is not correlated with core noise for the simple reason that jet noise is not even correlated with itself at different angles, for the reasons stated previously. However, it does not eliminate the possibility that core noise may interact with jet noise in an uncorrelated way, e.g., increase it by a certain amount. In fact, such interactions occur as studied in Ref. 6, but are rather small because the jet turbulence is not very sensitive to intial levels except possibly for unusually clean laboratory experiments. The fact that there is a large amount of jet engine noise data conforming to a single prediction method which does not take into account the interaction of core noise and jet noise must mean that such interactions are negligible in practice.

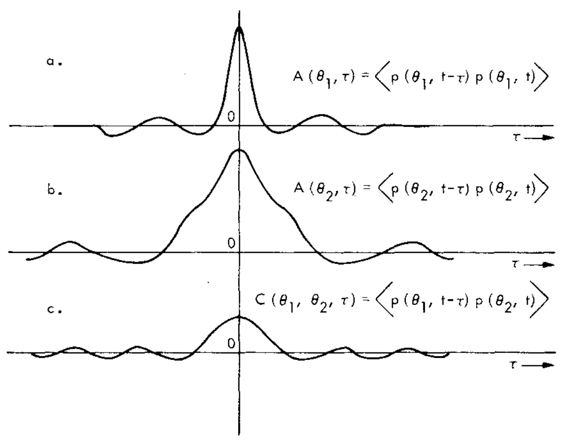

Fig. 1 a) Autocorrelation at θ_1; b) autocorrelation at θ_2; c) cross-correlation between signals from θ_1 and θ_2.

The peak cross-correlation of sound pressures at θ_1 and θ_2 is

$$C(\theta_1,\theta_2,0)=\langle p(\theta_1,t)p(\theta_2,t)\rangle$$
$$=\langle[p_J(\theta_1,t)+p_C(\theta_1,t)]\,[p_J(\theta_2,t)+p_C(\theta_2,t)]\rangle$$
$$=\langle p_J(\theta_1,t)p_J(\theta_2,t)\rangle+\langle p_C(\theta_1,t)p_C(\theta_2,t)\rangle$$
$$=0+[A_C(\theta_1,0)A_C(\theta_2,0)]^{1/2} \qquad (3)$$

The first term in the above equation is zero because jet noise at widely separated angles is essentially uncorrelated. Unlike jet noise, core noise is fully correlated; hence, the second term of Eq. (3) is the geometric mean of the two mean-square pressures at θ_1 and θ_2.

The directivity of pure jet noise is well established. Let α denote the ratio of mean-square pressures of jet noise at the two angles θ_2 and θ_1. Thus,

$$\alpha=A_J(\theta_2,0)/A_J(\theta_1,0) \qquad (4)$$

Similarly, let the ratio of core noise sound pressures be denoted by β which must be determined.

$$\beta=A_C(\theta_2,0)/A_C(\theta_1,0) \qquad (5)$$

Quantities referring to θ_2, in Eqs. (2) and (3) can be eliminated by using Eqs. (4) and (5). Then the following equations are obtained:

$$A(\theta_2,0)=\alpha A_J(\theta_1,0)+\beta A_C(\theta_1,0) \qquad (6)$$

and

$$C(\theta_1,\theta_2,0)=\sqrt{\beta}A_C(\theta_1,0) \qquad (7)$$

Equations (1), (6), and (7) can then be solved for $A_J(\theta_1,0)$, $A_C(\theta_1,0)$, and β using the measured quantities $A(\theta_1,0)$, $A(\theta_2,0)$, $C(\theta_1,\theta_2,0,)$, and the known quantity α.

Experimental Data and Discussion

Experiments have been performed in which nitrogen gas at ambient temperature flowed through a nozzle which had an exit diameter of 2.58 cm. The upstream plenum was a 1-m-long tube of 3.18 cm diam. The gas flowed radially inward into the plenum through three tubes spaced 120 deg apart at the entrance and as a consequence produced internal turbulence and noise. No attempt was made to produce additional turbulence or suppress existing turbulence and the facility was nominally clean except that the flow entered at right angles to the axis of the plenum.

Experiments were conducted at jet velocities between 25 and 300 m/s, and the noise was measured by an array of eight microphones located in a rectangular array in the far field. The data were recorded on an FM tape recorder and were processed later using a high-speed correlator. The eight microphones located at coordinates (r,θ) indicated sound pressures as shown in Table 1.

Samples of correlations are shown in Figs 2-7. In Figs 2-4 the correlations are for a comparatively high subsonic jet velocity, $U_j=250$ m/s. It is seen in this case that the cross-

Table 1 Microphone coordinates

No.	r,cm	θ,deg
1	269.5	119.5
1	239.5	101.7
3	234.5	90.0
4	248.0	71.0
5	291.0	53.7
6	360.5	40.6
7	433.5	32.7
8	395.5	23.5

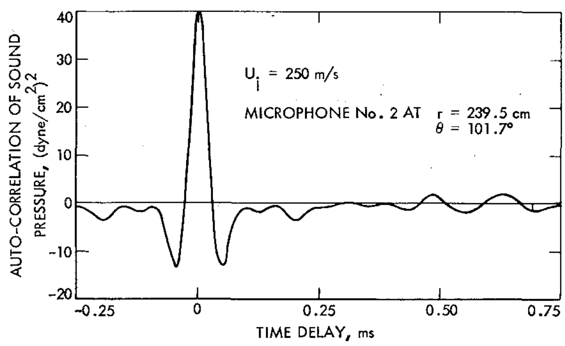

Fig. 2 Autocorrelation of sound pressure at $\theta = 101.7$ deg for jet velocity $U_j = 250$ m/s.

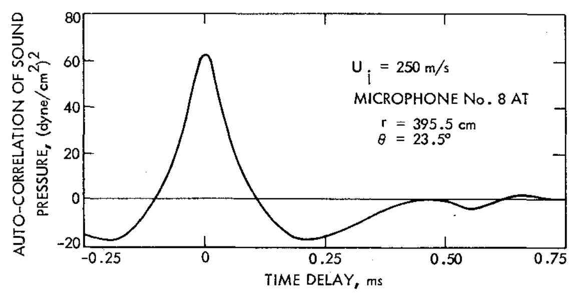

Fig. 3 Autocorrelation of sound pressure at $\theta = 23.5$ deg for jet velocity $U_j = 250$ m/s.

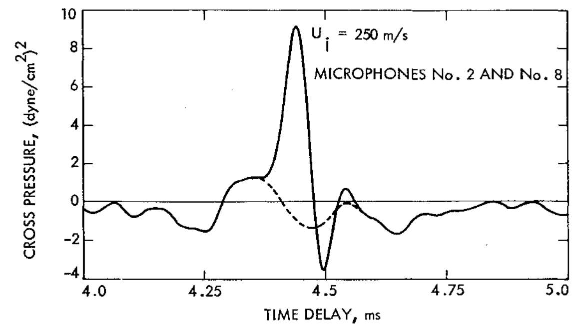

Fig. 4 Crosscorrelation of sound pressures between microphones 2 and 8 at $\theta = 101.7$ and 23.5 deg for $U_j = 250$ m/s.

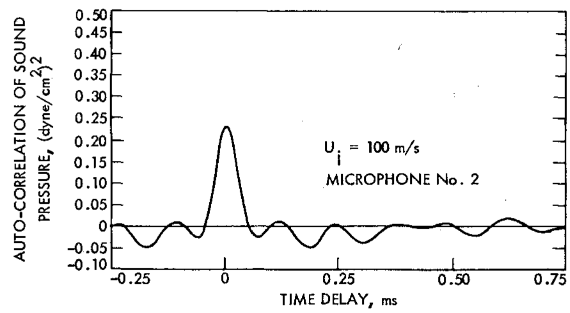

Fig. 5 Autocorrelation of sound pressure at $\theta = 101.7$ deg for jet velocity $U_j = 100$ m/s.

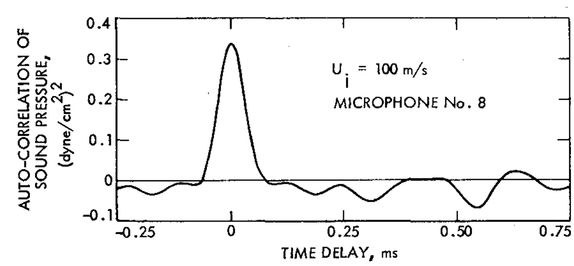

Fig. 6 Autocorrelation of sound pressure at $\theta = 23.5$ deg for jet velocity $U_j = 100$ m/s.

correlation is small compared to the two autocorrelations, i.e., 9 compared to 40 and 62. The width of the autocorrelation in Fig. 2 at $\theta = 101.7$ deg is narrow, indicating a higher frequency content compared to the one at $\theta = 23.5$ deg in Fig. 3, which is much wider and is therefore of lower frequency. The cross-correlation has approximately the same width as the autocorrelation in Fig. 2. This means that the spectra of jet noise resulting from Fig. 2 and the core noise resulting from Fig. 4 are quite similar to each other. The dotted lines in Fig. 4 indicate the trend of the contribution of jet noise to the cross-pressure. This is seen to be not quite symmetric about the peak. If this function were made to be symmetric about the peak, which can be done, the small contribution of jet noise to the cross-pressure would be eliminated.

The second sample of data taken at a lower jet velocity, $U_j = 100$ m/s, is shown in Figs. 5-7. In this case the magnitudes of the cross-pressure are comparable to those of the autocorrelations. Here, the core noise dominates and the shapes of all three functions look alike. Sound pressures were corrected to a fixed radial distance of 100 cm by multiplying the autocorrelations by $(r_1/100)^2$, $(r_2/100)^2$ and the cross-correlations by $r_1 r_2/(100)^2$.

A sample of data acquired by two microphones located at angles of 101.7 and 23.5 deg to the jet axis is shown in Table 2. In the table, subscript *1* refers to 101.7 deg and subscript *2* to 23.5 deg. Quantities A_1 and A_2 are the mean-square sound pressures in $(\text{dyne/cm}^2)^2$ at a radial distance equal to 1.0 m from the nozzle exit. C is the mean-square cross-pressure between the two microphones; and the quantity α is the ratio

Table 2 Microphone data

U_j	Correlation coefficient	A_1	A_2	C	α	β	A_{C1}	A_{J1}	A_{J2}	A_{C2}
250	0.185	228	978	87.4	8.71	0.506	123	105	916	62.2
200	0.407	62.8	188	44.1	6.03	1.03	39.7	23.0	13.9	49.1
150	0.657	11.1	34.8	12.9	4.47	2.59	8.02	3.12	13.9	20.8
100	0.818	1.32	5.27	2.16	2.57	4.38	1.03	0.292	0.750	4.51
70	0.900	0.232	0.782	0.382	1.74	3.62	0.201	0.031	0.054	0.727

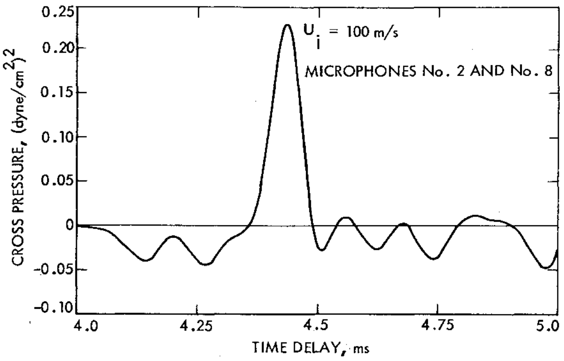

Fig. 7 Cross-correlation of sound pressures between microphones 2 and 8 at $\theta = 101.7$ and $\theta = 23.5$ deg at jet velocity $U_j = 100$ m/s.

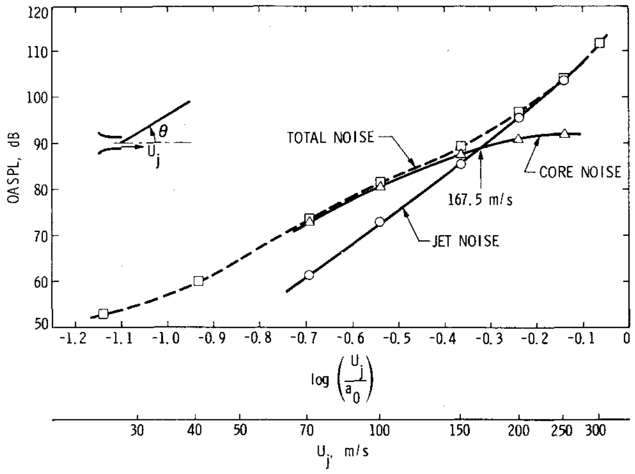

Fig. 8 Separation of OASPL at $\theta = 23.5$ deg into jet noise and core noise vs jet velocity U_j.

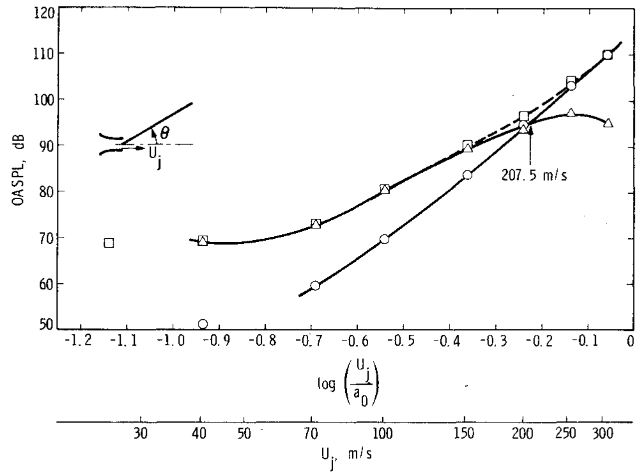

Fig. 9 Separation of OASPL at $\theta = 40.6$ deg into jet noise and core noise vs jet velocity U_j.

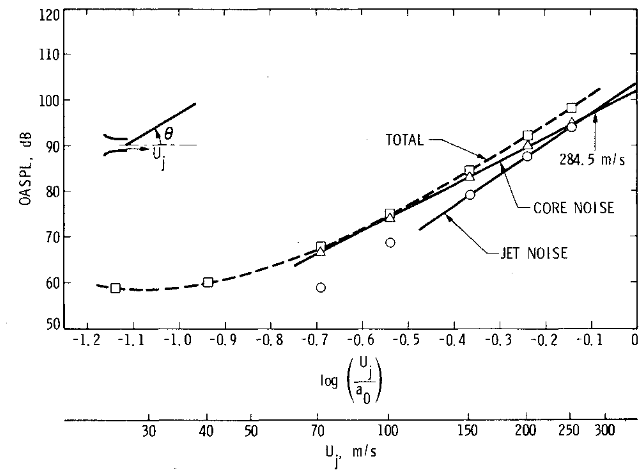

Fig. 10 Separation of OASPL at $\theta = 101.7$ deg into jet noise and core noise vs jet velocity U_j.

of jet noise at position 2 to jet noise at position 1 and is known because the directivity of pure jet noise is well established. The values of α were evaluated using the data in the SAE document on Aerospace Recommended Practice, ARP876. The quantities A_{C1}, A_{C2}, and A_{J2} are calculated from a knowledge of A_1, A_2, C, and α. At high velocities, the correlation coefficient is small and at large angles (subscript *1*) the values of A_{C1} and A_{J1} are comparable. At angles closer to the jet axis (subscript *2*), however, jet noise dominates. At low velocities, it is seen that core noise exceeds jet noise at both angles.

The results are presented as plots of overall sound pressure levels (OASPL) in decibels vs log (U_j/a_0). The quantity U_j is the mean jet velocity at the nozzle exit and a_0 is the ambient speed of sound. Figure 8 shows the total noise as well as jet noise and core noise components at an angle $\theta = 23.5$ deg with respect to the jet axis. It is interesting to note that the two distributions of jet noise and core noise of monotonically varying slopes add to produce the total noise whose slope is not monotonic with log (U_j/a_0). The scatter in the experimental points is less than ½ dB. In this figure, jet noise and core noise are equal at $U_j = 167$ m/s. Figures 9 and 10 show a similar separation at larger angles of $\theta = 40.6$ and 101.7 deg.

The same data are presented in Fig. 11 to show the behavior of core noise at three angular locations. At low velocities, core noise has a preferential forward directivity and this is seen to shift gradually to higher angles as U_j increases. Refraction by high-speed flow is one of the mechanisms responsible for this effect. A typical slope of the core noise relation is 5.15 indicating that the intensity of core noise is proportional to $U_j^{5.15}$.

Figure 12 shows the jet noise contribution to OASPL at the same three angles. Typical slopes vary between 7.55 at 101.7 deg and 9.05 at 40.6 deg. Such values are typical of pure jet noise. In Figs. 11 and 12, there are two sets of data points for the position $\theta = 101.7$ deg. These were obtained from the two cross-correlation analyses using two pairs of microphones located along angles of 101.7 and 23.5 deg and along angles of 101.7 and 40.6 deg. The two sets of data agree very well.

In the present experiments, as seen from Figs. 8-10, the cross-over point where core noise is equal to jet noise moves progressively to higher jet velocities as the angle to the jet axis increases. This is interesting because such cone noise at high jet velocities will undergo further amplification by flight and may be responsible for the existence of sideline noise which does not diminish in a manner expected of jet mixing noise.

At values of OASPL below about 65 dB, the experimental data are contaminated by electronic noise. This noise is uncorrelated between different channels and shows up as jet noise in this method. Of course, this contamination could be eliminated by the use of more sensitive microphones.

Extension of Method to Obtain Spectral Information

The method of separating jet noise and core noise as presented can also be extended to obtain spectral information. Equations (1-3) are modified to nonzero values of τ by changing 0 to τ. When these three equations are Fourier transformed, equations for the spectral densities such as the

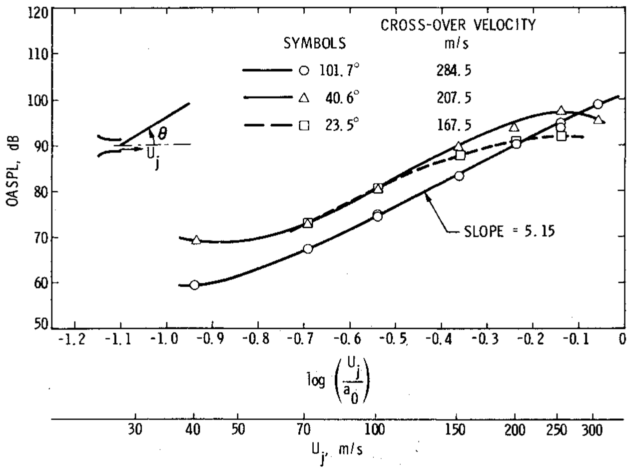

Fig. 11 Variation of core noise vs U_j at different angles to jet axis.

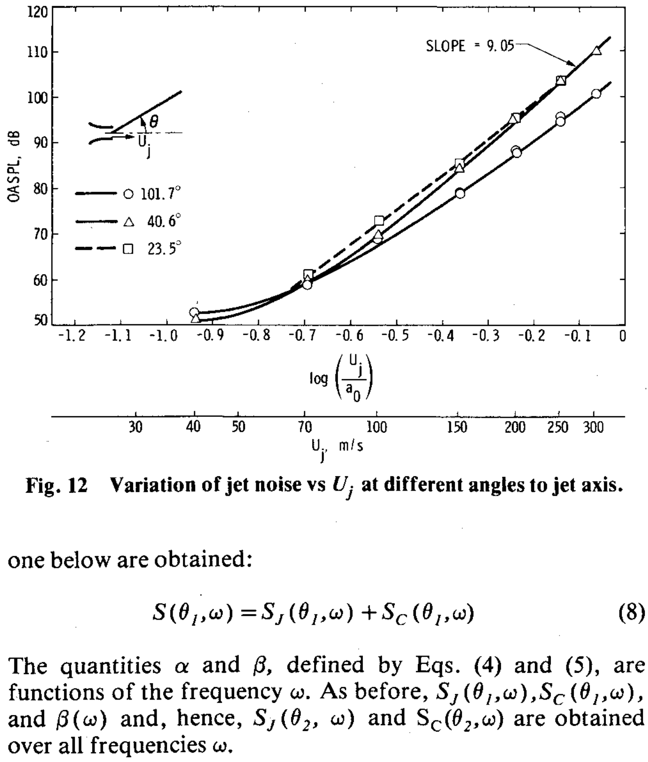

Fig. 12 Variation of jet noise vs U_j at different angles to jet axis.

one below are obtained:

$$S(\theta_1,\omega) = S_J(\theta_1,\omega) + S_C(\theta_1,\omega) \tag{8}$$

The quantities α and β, defined by Eqs. (4) and (5), are functions of the frequency ω. As before, $S_J(\theta_1,\omega)$, $S_C(\theta_1,\omega)$, and $\beta(\omega)$ and, hence, $S_J(\theta_2,\omega)$ and $S_C(\theta_2,\omega)$ are obtained over all frequencies ω.

Extension to Case of Jets Immersed in Outer Stream

The data obtained in a free-jet simulation facility can be analyzed using Eqs. (1-7). The effect of refraction by the outer flow modifies α and $\alpha(\omega)$ and this can be obtained in a straightforward manner either by geometric acoustics or by calibration.

Extension to Case of Noise from Moving Aircraft

The analysis can also be extended to an aircraft noise source which moves along a straight line (the x axis) as shown in Fig. 13. The wavefront shown by the larger circle corresponds to the radiation emitted at time t_1. This wavefront has travelled at the speed of sound a distance equal to its radius. The smaller circle centered around B refers to the radiation that left B at time t_2, and has traveled for a time such that the distance is equal to the radius of the smaller circle divided by the ambient speed of sound. C represents a point midway between A and B. It is observed that the waves are packed more closely in the direction of motion and are loosely packed in the opposite direction. Microphones placed at D_2 and D_1 would sense sound signals shown in the sketch which are

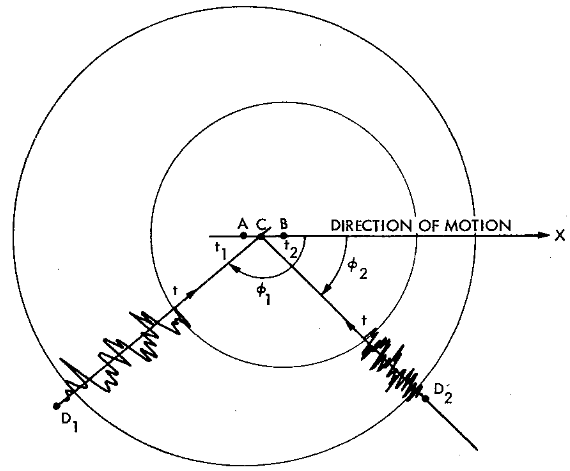

Fig. 13 Time signals of sound pressure at different angles to direction of motion from moving source showing changes due to compression of wavefronts in direction of motion.

simply the spatially distributed pressures sweeping outward past the microphones. Frequencies at acute angles are increased and frequencies at obtuse angles to the direction of motion are decreased in accordance with the well-known Doppler effect. At the angle ϕ, the time duration Δt_e of the emitted signals is compressed to the observer interval

$$\Delta t_0 = \Delta t_e (1\text{-}M\cos\phi) \tag{9}$$

M is the aircraft velocity divided by the ambient speed of sound. At $\phi = 90$ deg there is no change in the time interval. To process this signal, the speeds of playback of the signals must be decreased by the same Doppler factor. In the direction ϕ_2, the playback speed of the recorder is reduced to $W/(1-M\cos\phi_2)$ where W is the speed of the original recording. In the direction ϕ_1, it is correspondingly increased to $B/(1-M\cos\phi_1)$. These signals would be free of the influence of Doppler compression and can be cross-correlated in exactly the same manner as for the static sound source. As a practical point, it may be noted that continuous variation of speed is uncommon in tape recorders and the operation of speed changing is readily accomplished by a minicomputer which can store data and reproduce it with a different time scale, move the origin in time, and cross-correlate signals with ease.

There is another effect due to motion which changes the magnitude of sound in addition to the time compression effect discussed above. This effect has the form

$$p = \frac{1}{4\pi r}\,\frac{q'(t')}{(1-M\cos\phi)^N} \tag{10}$$

where q' is the time derivative of the source fluctuation (i.e., source of acoustic potential) and t' is the retarded time which is the observation time minus the time of travel. The quantity r is the distance from the source position at emission to the location of observation, and N is an index that depends on the type of source, i.e., monopole, dipole, etc.

More accurately, changes in pure jet noise due to flight are well represented by the correlations given by Cocking.[7] These are

$$\Delta\text{OASPL} = 10\log(1+M_a\cos\phi) - 10(\delta_j - \delta_{\text{rel}})\log(\rho_0/\rho_j)$$

$$+\,10\log\left[(V_j/V_{\text{rel}})^{5.4}(C_{V_j}/C_{V_{\text{rel}}})\right] \tag{11}$$

Here the Doppler factor C, is given by

$$C = [(1 - M_C \cos\phi)^2 + 0.09 M_C^2]^{-1.9} \qquad (12)$$

and M_C, the convection Mach number, is given by

$$M_C = 0.65 V_{\text{rel}} / a_0 \qquad (13)$$

In the region $\phi \geq 90$ deg, a simpler correlation is recommended which replaces $(C_{V_j}/C_{V\text{rel}})$ in Eq. (11) by unity. The same equations apply for changes of spectral densities as well. For conventional coaxial jets, the same equations apply with the larger jet velocity (i.e., the core velocity) playing the role of the single round jet. In other words, the changes in noise are independent of the bypass flow. Equations (11-13) together with the predicted behavior of static jet noise are sufficient to describe the jet noise. The method of separation of core noise and jet noise can be accomplished by processing signals stretched or squeezed in time in accordance with Eq. (9).

Summary and Conclusions

It has been demonstrated by experiments that the analysis based on cross-correlation of the sound pressures in the far field enables one to separate the mean-square pressures of core noise and of jet noise. The method has been extended to separate the spectral components and also to determine the effects of a surrounding flow simulating forward motion. In addition, the analysis of flyby data acquired by several microphones on the ground simultaneously can be performed in a straightforward manner.

The analysis was shown to be internally consistent because the separation of total noise into core noise and jet noise does not depend upon the choice of the microphone positions, provided only that the angle between them is large.

The experiments were conducted at jet velocities between 25 and 300 m/s, and the noise was measured by eight microphones located in a rectangular array in the far field at angles between 23.5 and 102 deg relative to the downstream axis of the jet. At low jet velocities, core noise has a preferential forward directivity and this was seen to shift gradually to higher angles as jet velocity was increased. Refraction by high-speed flow is one of the mechanisms responsible for this effect. A typical slope of the core noise relation is 5.2, indicating that the intensity of core noise is proportional to $U_j^{5.2}$. Typical slopes for jet noise varied between 7.5 and 9.0 depending upon angle. The crossover point where core noise is equal to jet noise moves progressively to higher jet velocities as the angle to the jet axis increases. This is interesting because such core noise at high jet velocities will undergo further amplification by flight and may be responsible for the existence of sideline noise which does not diminish in a manner expected of jet mixing noise.

It is also possible to separate jet noise and core noise without using information about the directivity of either because an extra microphone supplies three correlation functions while containing only two unknowns. If more than three microphones are used, internal consistency of the data reduction can be verified.

Acknowledgment

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