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Spectral Broadening Effects in Open Wind Tunnels in Relation to Noise Assessment

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Wind tunnel tests were performed in the 10th scale DNW pilot tunnel to assess the effects of the turbulent shear layer on pure tone sound, propagating from a model in the flow to a microphone outside the flow. The effect is very small when ⅓-octave analysis is used, as the spectral broadening of the tone is in general smaller than a ⅓-octave bandwidth. This means that all sound energy is propagated through the shear layer and that only the usual refraction corrections have to be used. It is concluded that sound scattering by shear layer turbulence does not restrict the use of large open wind tunnels, such as DNW, when full-scale effective perceived noise levels are to be determined.

Nomenclature

f	= frequency, Hz, s^{-1}
M	= test-section Mach number
u'	= fluctuating velocity, ms^{-1}
U	= test section velocity, ms^{-1}
x	= streamwise distance, m
δ	= shear-layer thickness, m
λ	= wavelength of sound, m

Introduction

THE effects of forward speed on aircraft noise are of great importance. Many of these effects can be investigated in specially adapted wind tunnels. Acoustic testing on models in open jet wind tunnels has some important advantages over testing in closed test section wind tunnels.[1] The German-Dutch wind tunnel DNW (Fig. 1) can be operated in the open jet mode, providing a jet length of about 20 m, with an 8×6 m^2 cross section (Fig. 2). Preliminary check-out measurements performed in February 1980 have revealed that the background noise level of the open jet mode of the DNW is the lowest when compared to other large wind tunnels. This means that practically all important types of aeroacoustic experiments can be executed (Fig. 3).

The advantages of open jet acoustic testing are 1) a large distance to the source is possible (far field), 2) the microphones can be located outside the flow (no microphone flow noise) and 3) a better anechoic environment can be made as no flow along the acoustic treatment is present. However, the presence of the turbulent shear layer at the jet boundary has effect of the sound propagation to the microphone by refraction, reflection, and scattering.

Refraction effects can accurately be corrected for by using Snell's law such as described by Amiet[2] and Ahuja et al.[3] Perulli[9] suggested that the effect of reflection at the shear layer is minor, and that, indeed, most of the sound energy is propagating through the layer.

Scattering was found to have a large effect on the propagation of high frequency pure tones through the turbulent shear layer.[4] The effect consists of a spectral broadening and a decrease in noise level at the tone-frequency band, and is increasing with higher frequency, larger shear layer thickness, and higher flow Mach number.[3,5-7] Furthermore, a "smoothing" effect on directivity can be expected.

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In large wind tunnels such as the DNW thick shear layers are present. For scaled-down models, high-frequency noise sources will be used. So, for pure tones, large scattering effects are to be expected, in particular at the higher velocities attainable in the DNW (80 ms^{-1}). For broadband noise, it is already known that shear-layer scattering effects can be neglected (e.g., Refs. 3 and 4).

All investigators using pure tone sound applied narrowband analysis. For aircraft noise certification, however, ⅓-octave analysis has to be used, even if tones are present. A tone correction procedure is prescribed, for which, in principle, the ⅓-octave band of the tone is compared with the adjacent ⅓-octave bands. This procedure also holds for a pure tone at a frequency just between two ⅓ octaves. So, for wind-tunnel noise tests also, ⅓-octave analysis has to be used if the results are to be converted to full-scale equivalent perceived noise levels. It should be recalled that the method of

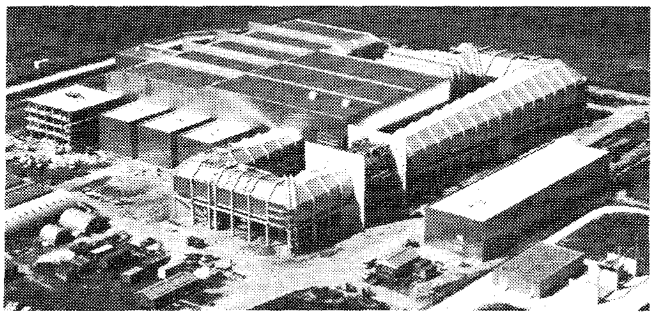


Fig. 1 Aerial view of the DNW (KLM-Aerocarto).

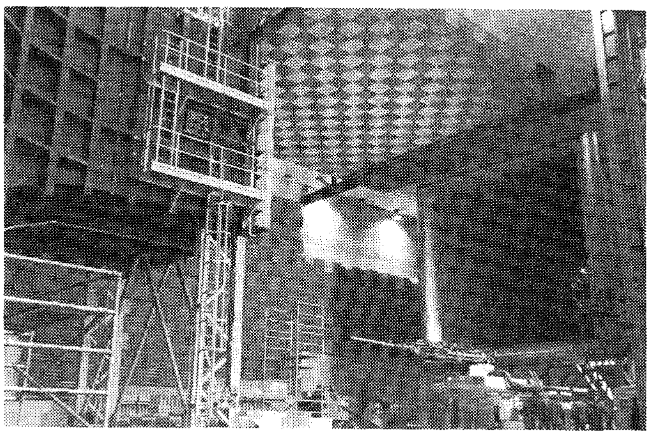


Fig. 2 DNW open jet arrangement.

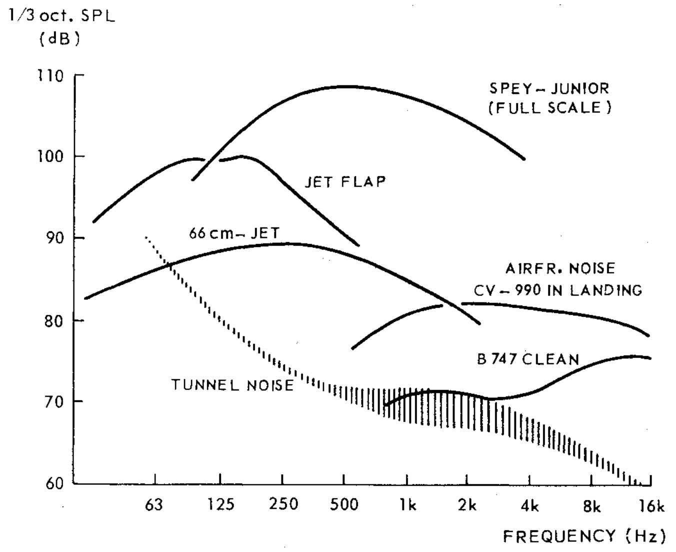


Fig. 3 Types of noise measurements in DNW at 80 ms^{-1} (15 m sideline).

converting narrow band results into ⅓-octave bands does not comply to the standards set for ⅓-octave band measurements.

However, no information was available concerning the way the shear-layer turbulence affects the pressure level at tone frequency when ⅓-octave analysis is used instead of narrow-band analysis. When the broadening is less than ⅓-octave and all energy is transmitted through the layer, the effect of scattering, for many practical applications might be small or negligible.

To obtain some information about the described problems, a series of tests was specified for the 10th scale DNW pilot tunnel. In these tests, the same values of the essential parameters as those occurring in the full scale DNW were chosen.

An essential parameter is the ratio of the wavelength of the sound λ, and the scale of the turbulence.[3] The dimensions of the large, most energy containing eddies are of the order of the shear-layer thickness δ. Furthermore, it can be expected that the absolute intensity of the turbulence is an important parameter. This is assumed to be proportional to the flow Mach number M (so, $u^1/U=$const).

This means, for the model tests, that the frequencies have to be a factor of 10 higher than in the DNW, and that the same Mach numbers are to be used.

For the experiments, pure tone noise was generated and the signal was measured with ⅓-octave analysis, and for comparison, with narrow-band analysis. A source with a rather strong directivity was used to enhance possible effects of directivity spreading.

Test Setup

In the 10th scale DNW pilot tunnel, high frequency sound had to be generated to simulate DNW conditions. A simple dome tweeter loudspeaker could be used up to 40 kHz, thus corresponding to 4 kHz in the DNW. The speaker was flush mounted in a fairing inside the flow. The axis of this speaker was perpendicular to the flow direction, and the microphone was placed outside the flow (Fig. 4).

A shear-layer thickness variation was obtained by traversing the loudspeaker/microphone combination downstream with their relative position kept the same. This was performed by mounting both on a heavy traversing mechanism. The microphone was positioned in the direction of maximum noise from the speaker (i.e., the main lobe), using in the cases with flow, the theoretical corrections for directivity shift and refraction angle. The turbulence intensity was varied by using different flow velocities.

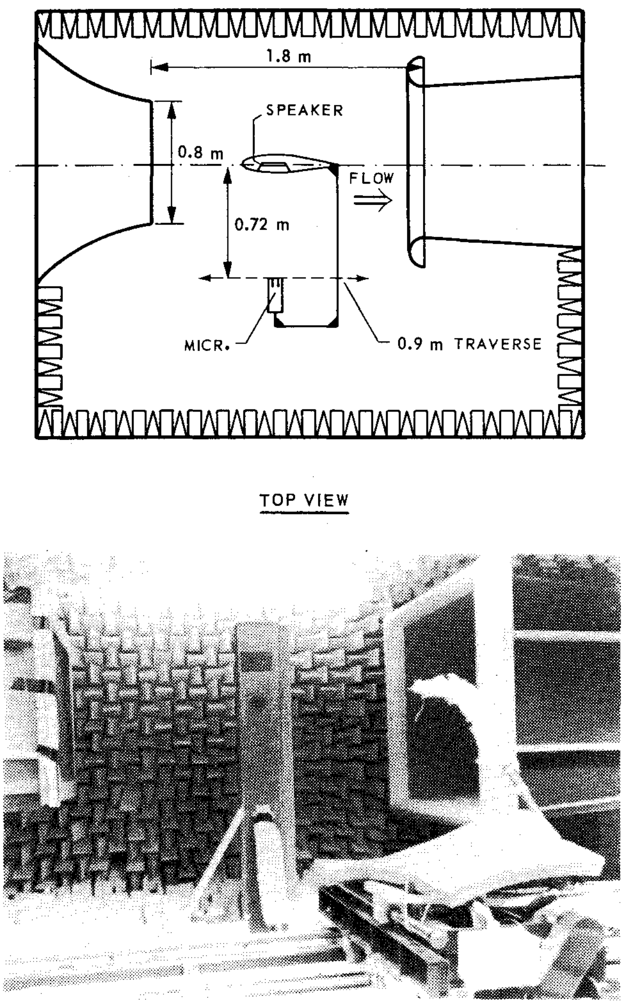


Fig. 4 Test setup for shear layer scattering tests.

A tone generator was used to create pure tones at frequencies about equal to ⅓-octave band center frequencies. Frequencies of 10, 20, 30, and 40 kHz, and test section velocities of 0, 40 and 80 ms^{-1} were used.

The microphone signal was analyzed with a ⅓-octave filter. The ⅓-octave band sound pressure level was plotted against the x position of the speaker/microphone combination. This was done also for the narrow-band measurements. For this, a real-time analyzer was used. For each x position the data were averaged 8 times for 40 ms^{-1} test-section velocity, and 16 times for 80 ms^{-1} velocity. A line was faired through the data points of the measured x position. A resolution bandwidth of 125 Hz was used for all frequencies.

Sound Source Characteristics

The characteristics of the source should be insensitive to the presence of airflow. This was verified by traversing a microphone with nose cone, in the flow, in the streamwise direction along the speaker, at a minimum distance of 0.2 m (Fig. 5). With this procedure no direct directivity plot is obtained, as the distance to the source is not constant. The deviation is, however, small, about 0.3 dB at a viewing angle of 15 deg and 1.2 dB at 30 deg. It can be seen that, in particular at the higher frequencies, the source was highly directional but that the directivity pattern was hardly influenced by the flow. At a small distance, an effect of the source size (0.1 m) was found. At the highest frequencies and 80 ms^{-1} test-section velocity, the results are hampered by a high background noise, due to flow noise around the microphone and "airframe" noise of the speaker fairing. Furthermore, the convection of the sound waves by the flow is

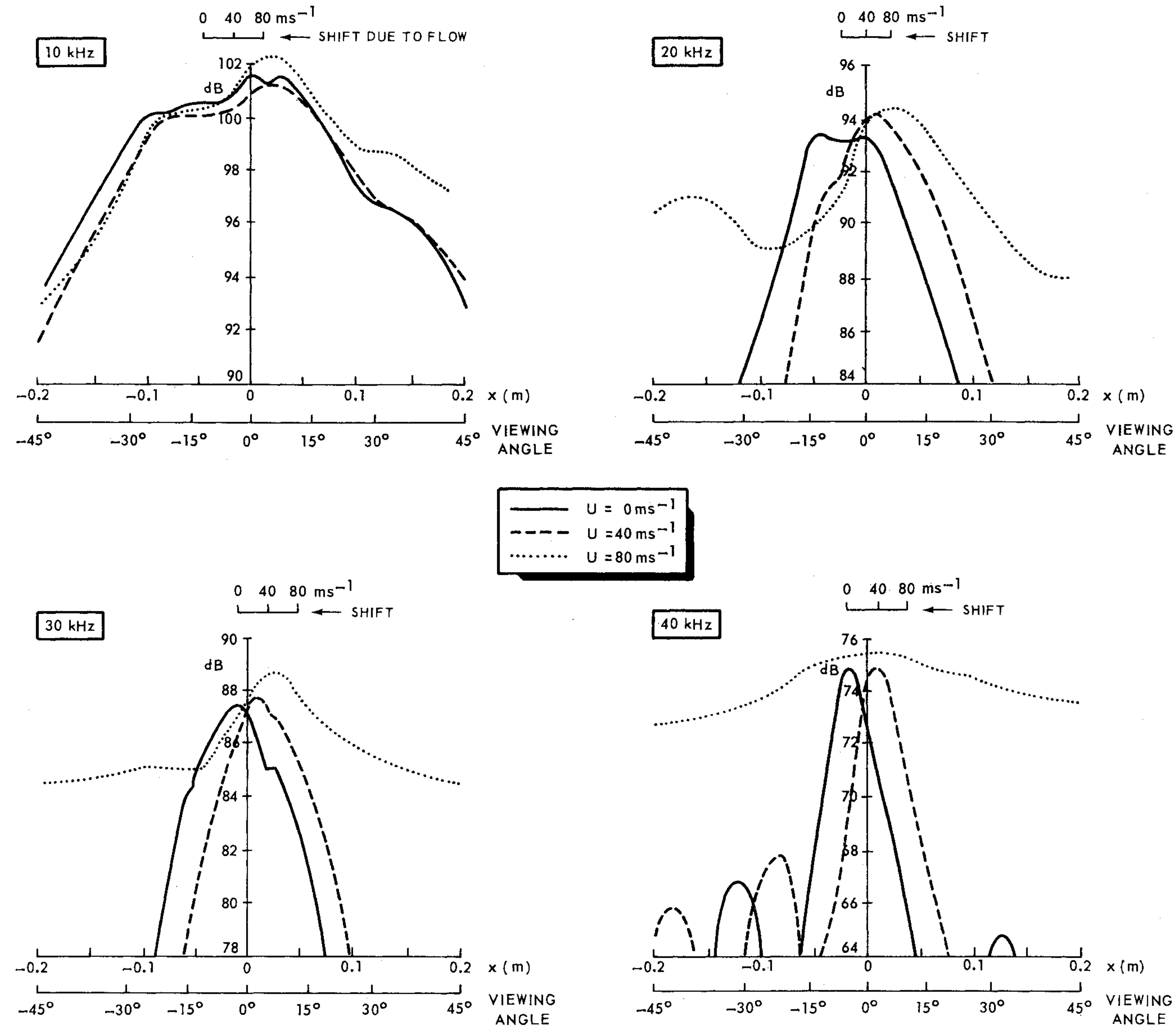


Fig. 5 Directivity of pure tone noise source (dome tweeter) at different flow velocities, ⅓-octave band measurements in the flow.

clearly visible in Fig. 5 and is comparable to the calculated directivity "shift."

It was concluded that the dome tweeter could be used for sound emission angles of about 0 deg at 0 ms^{-1} and the corresponding corrected angles at 40 and 80 ms^{-1} velocity (being 6.7 and 13.2 deg, respectively). At these angles, the changes due to flow of the radiated sound energy were smaller than 1 dB. This was found acceptable for these experiments.

To check the results, some tranverses of the microphone were made outside the flow. In this case shear-layer effects were present. No anomalies with respect to source directivity were found, except at 30 kHz. At this frequency irregular deviations up to 2 dB occurred, possibly caused by room or tunnel reflections of unknown origin.

Results

Qualitative Narrow-Band Scattering Results

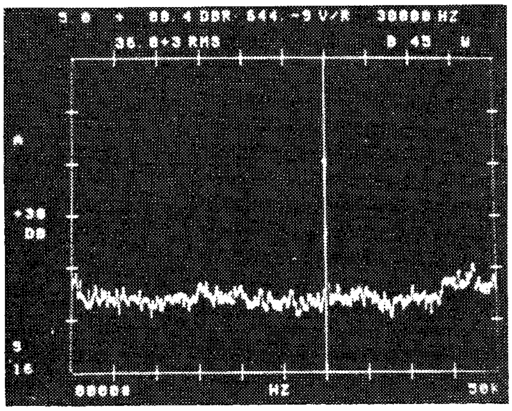
The narrow-band real-time frequency analyzer was used in a frequency range from 0 to 50 kHz. The number of lines used was 400 and the resolution bandwidth was 125 Hz. In Fig. 6, some examples are given of spectra for a 30 kHz tone measured outside the flow at 0 and 80 ms^{-1} test-section velocity.

At zero velocity, all sound energy is concentrated in the 30 kHz line, giving a sound pressure level of 88.4 dB. At 80 ms^{-1}, the sound energy is spread over several frequency bands, giving a reduction at the 30 kHz line down to 81.4 dB. This value was found after 16 times averaging. The lower picture in Fig. 6 gives the results of another measurement, taken shortly after the one giving a peak of 81.4 dB. It can be seen now that even after 16 times averaging, the sound energy peaks at a frequency "line" adjacent to the 30 kHz line, at the 30, 125 Hz line. The measured sound pressure level at 30 kHz is now 79.9 dB, and the level at 30, 125 Hz is some decibels higher. This gives a clear example of what can happen when narrow-band analysis is used in the presence of shear-layer scattering effects (in flight and open jet wind tunnel).

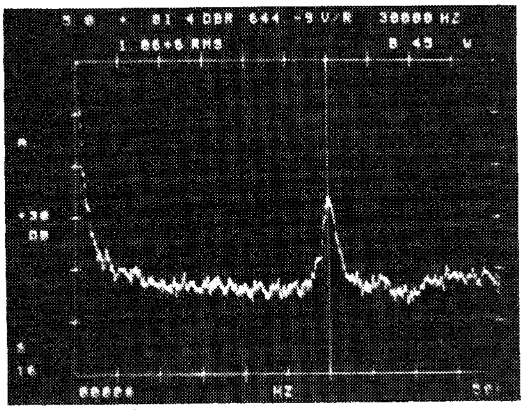
From the pictures it can be seen that the spectrum of the scattered signal has a more or less triangular shape when plotted in decibels. This appearance will be used later to calculate the broadening effects quantitatively.

Differences between ⅓-Octave and Narrow-Band Analysis

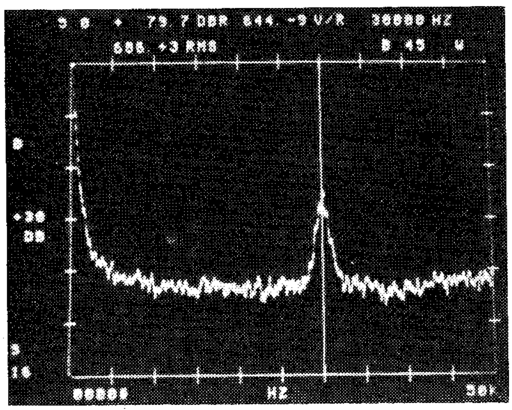
The scattering effects are defined as the decrease in decibels between the tone frequency band sound pressure levels without and with flow. These values were measured during



a) NO FLOW
PEAK NOISE 88.4 dB



b) 80 ms^{-1} FLOW VELOCITY
PEAK NOISE 81.4 dB
16× AVERAGING



c) 80 ms^{-1} FLOW VELOCITY
79.7 dB AT 30 kHz,
PEAK NOISE AT 30125 Hz
16× AVERAGING

Fig. 6 Typical frequency spectra of signal without/with flow, 30 kHz pure tone.

downstream traverses of the speaker/microphone combination (with a varying shear layer thickness) with narrow-band and ⅓-octave band analysis. The results are presented in Fig. 7. It can be seen in this figure that, for narrow-band analysis, the scattering effect is increasing with an increasing shear-layer thickness, except for the lowest velocity and frequency where the effect is virtually absent. As the apparent scattering effect was small when using ⅓-octave band analysis, it is concluded that directivity spreading and/or reflection back into the tunnel flow can be neglected for practical purposes.

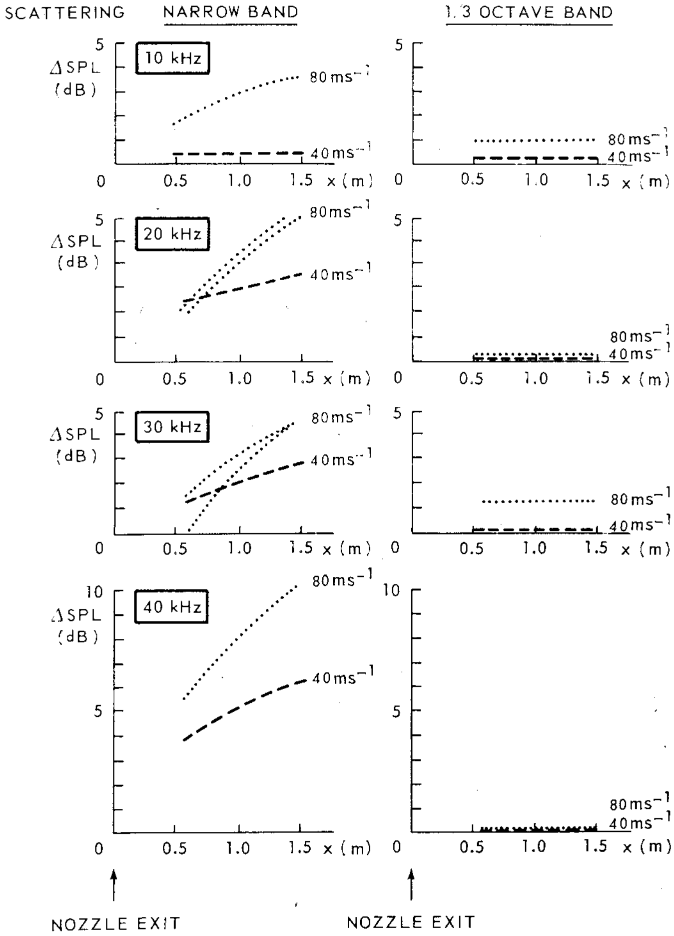


Fig. 7 Shear layer scattering effects for narrow-band and ⅓-octave band analysis, while traversing the speaker/microphone combination downstream, discrete tones.

In Fig. 8, the effects are given as a function of test-section velocity at two positions: the most upstream and downstream, at 0.45 and 1.38 m from the nozzle exit, respectively. Again, the effects were strong with narrow-band analysis, but small (less than 1 dB), with ⅓-octave band analysis.

Since it is assumed that the wavelength/shear-layer thickness ratio and the Mach number are the most important parameters in controlling the scattering process, it makes sense to group them in one parameter. The combination $M\delta/\lambda$ was found to be most appropriate. This parameter has also been used by Grosche[8] for his acoustic mirror tests.

The scattering effect is plotted against this diffraction parameter $M\delta/\lambda$ in Fig. 9. The shear-layer thickness δ was calculated with Goertler's theory as described in Ref. 5: $\delta = 0.16x$.

It can be seen that for narrow-band analysis the data are scattered but the tendency is clear: for values of $M\delta/\lambda$ above, say 0.5, strong scattering effects can be expected. When ⅓-octave band analysis is used, the effect is negligible, apart from the data scattering. When the narrow-band data are plotted for one frequency, the scatter is less (Fig. 10), as the 30 kHz results deviate from the other frequencies. This might be associated with the anomalies mentioned in the second paragraph on Sound Source Characteristics.

Quantitative Spectral Broadening

When all energy of the pure tone sound waves is transmitted through the shear layer and a triangular shape is assumed of the frequency spectrum of the scattered signal (Fig. 6), the spectral broadening can be calculated. These assumptions will hold for not too large scattering, e.g., for a

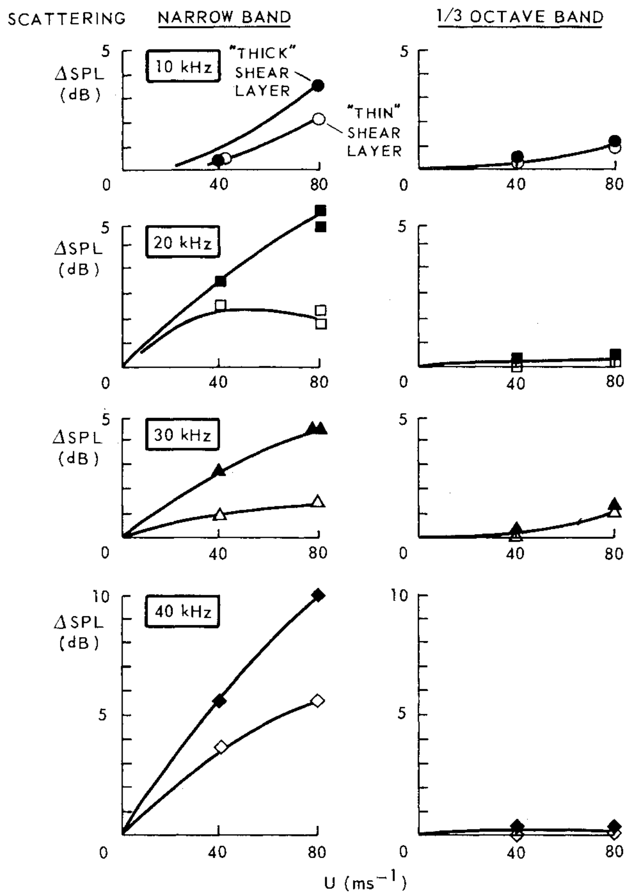


Fig. 8 Shear layer scattering for discrete tone signal, narrow-band and ⅓-octave band measurements, for different test section velocities.

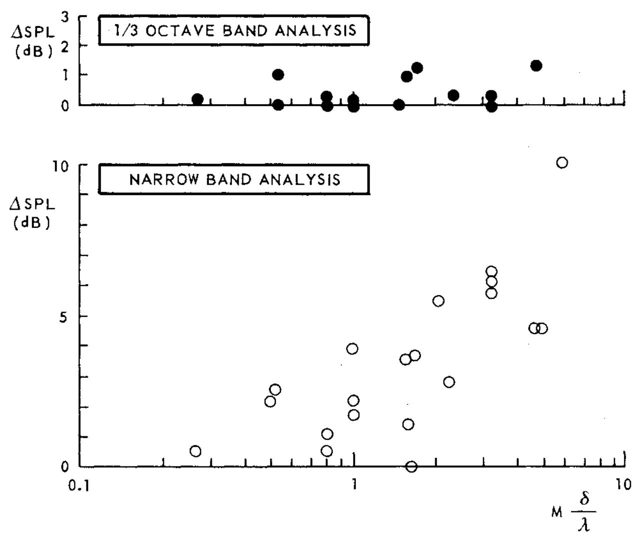


Fig. 9 Scattering effects as function of scattering parameter.

loss in peak noise level less than 10 dB. The triangular shape is not preserved at losses of 10 dB and higher.

Spectral broadening is defined as: the frequency bandwidth where the sound pressure levels differ less than 10 dB from the peak level of that bandwidth. For pure tone noise this width is equal to the analyzer bandwidth, in this case 125 Hz. The calculation procedure is given in the Appendix.

A consequence of the assumption is that the spectral broadening is in this case a function only of the loss in peak level. This is, in turn, a function of the scattering parameter ($M\delta/\lambda$) and the bandwidth that is used in the measurement.

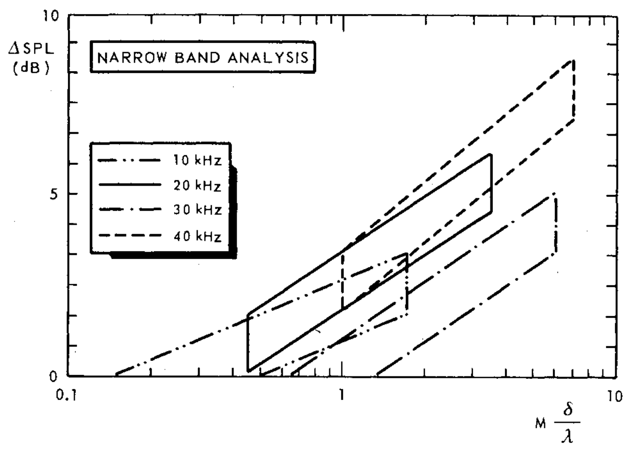


Fig. 10 Scattering effect for different frequencies.

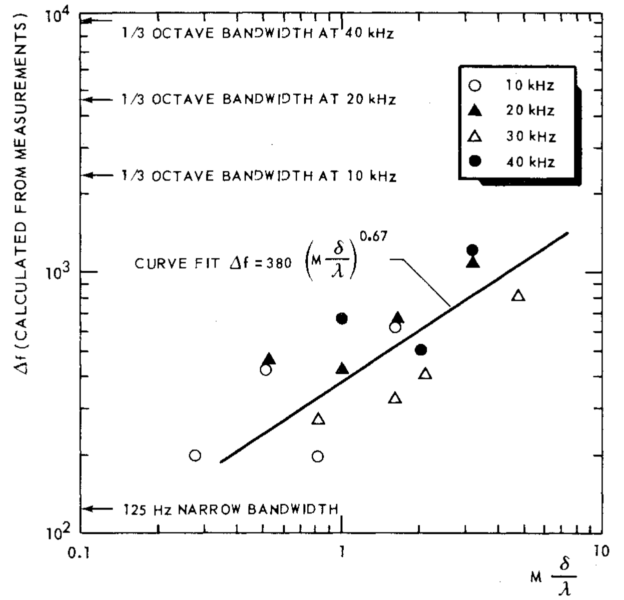


Fig. 11 Spectral broadening as a function of scattering parameter.

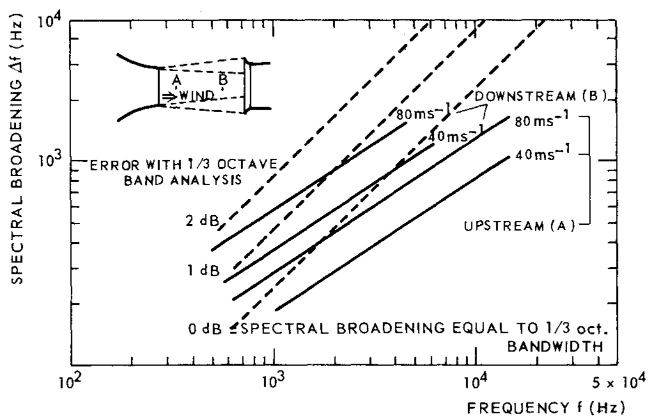


Fig. 12 Spectral broadening and scattering error converted to full scale DNW for pure tones, using curve fit of Fig. 11; 0 dB error means spectral broadening is equal to ⅓ octave.

In Fig. 11 the values of the spectral broadening, as calculated according to the Appendix, and using experimental values of the loss in peak level, are plotted against $M\delta/\lambda$. Also the ⅓-octave bandwidths are given of the frequencies that were used. It can be seen that the ⅓-octave bandwidths are several times larger than the amount of frequency broadening and that no scatter effect on the measured sound pressure level is to be expected.

These results were translated to DNW conditions and presented in Fig. 12, using the curve fit of Fig. 11. It appears that at higher frequencies the effect becomes smaller and at upstream position of the source no effect is found even at high velocities and frequencies. Downstream, deviations up to 1-1.5 dB are expected depending mainly on velocity, position, and frequency. At emission angles different from 90 deg, the path length through the shear layer is different from δ. In particular, in the rear quadrant spectral broadening may be larger than ⅓-octave bandwidth. It can be calculated, however, that the increase of the deviation in this case will be smaller than 1 dB compared to the deviation found at 90 deg.

Conclusions

From the results it can be concluded that for DNW conditions, the scattering and reflection effects of the open jet shear layer on pure tone propagation will be of minor importance when the sound is analyzed in ⅓-octave bands. This type of analysis is prescribed for the calculation of the annoyance levels (EPNL). Furthermore, it was already known that for broadband noise sources the shear layer scattering effects can be neglected. Therefore, noise data collected outside the flow of an open wind tunnel are well suited to estimate the corresponding full scale annoyance level (EPNL).

Appendix: Calculation of Bandwidths of Spectral Broadening

Let the sound pressure level of the pure tone signal be A (in dB) in one frequency band (Fig. A1), and the level of the scattered signal be B (in dB) at the same frequency band. When the frequency spectrum of the scattered signal has a triangular shape (as was found in the present tests), the difference between two adjacent frequency bands is constant in dB's and denoted here by C. It is assumed that the scattering of the sound waves is uncorrelated in frequency and time. This implies that sound energies can be added

$$10^{A/10} = 10^{B/10} + 2.10^{(B-C)/10} + 2.10^{(B-2C)/10} + \ldots$$

or

$$\tfrac{1}{2}\left(10^{(A-B)/10} - 1\right) = 10^{-C/10} + 10^{-2C/10} + 10^{-3C/10} + \ldots$$
$$= \frac{10^{-C/10}}{1-10^{-C/10}}$$

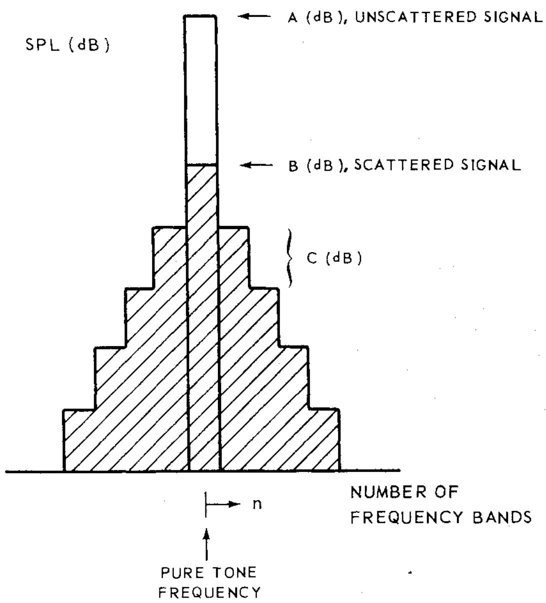


Fig. A1 Assumed shape of spectral broadening.

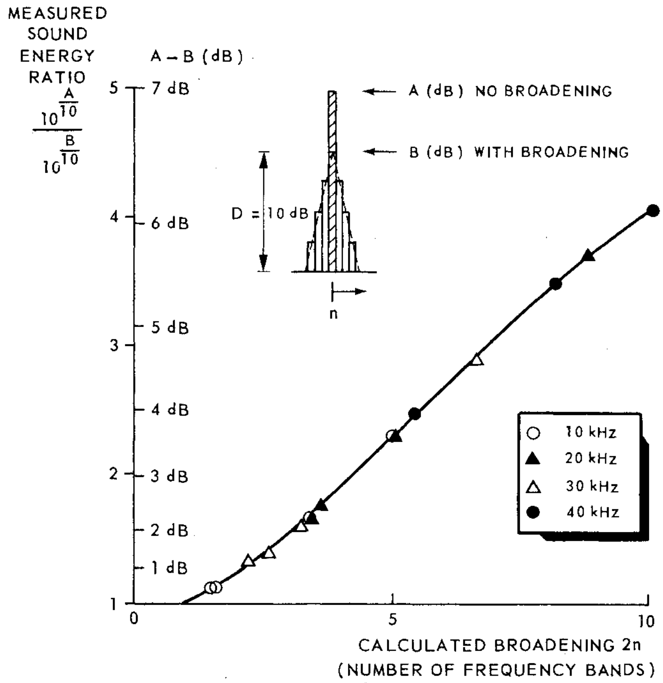


Fig. A2 Calculated spectral broadening, 125 Hz bandwidth.

A and B are measured, C can be calculated

$$C = -10 \log\left[\tanh\left\{\frac{1}{20}(A-B)\ln 10\right\}\right]$$

We are, however, interested in the frequency bandwidth at a sound pressure level of, say $B-D$ dB. When the number of bands is $2n$ (Fig. A1), we find

$$2n = 2D/C$$

Calculated results are given in Fig. A2. In this figure, the number of frequency bands of the broadening is given at a noise of 10 dB below the central frequency band noise level, i.e., $D = 10$ dB.

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