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Publisher's version / Version de l'éditeur:

Journal of the Acoustical Society of America, 77, 2, pp. 557-566, 1985-02

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SOUND FIELDS NEAR EXTERIOR BUILDING SURFACES

by J.D. Quirt

ANALYZED

Reprinted from
Journal of the Acoustical Society of America,
Vol. 77, No. 2, February 1985
p. 557 - 566

DBR Paper No. 1275
Division of Building Research

Price \$1.00

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RÉSUMÉ

La mesure de la transmission du son au travers de la façade d'un bâtiment exige la détermination de la puissance acoustique incidente. L'interprétation des mesures du niveau de pression acoustique près d'une façade est toutefois compliquée par les phénomènes d'interférence entre les ondes acoustiques incidentes et celles qui sont réfléchies par la façade. Des données expérimentales et un modèle mathématique simple sont utilisés pour examiner les effets systématiques liés aux réflexions produites par une grande façade plane et, ultérieurement, pour étudier les déviations par rapport à cette situation simple. Bien que le motif initial de ces travaux ait été l'étude des problèmes liés à la mesure de la transmission du son au travers des façades, de nombreux résultats sont applicables à d'autres situations qui nécessitent la mesure du bruit près d'une surface hautement réfléchissante.

CISTI / ICIST

3 1809 00210 4732

Sound fields near exterior building surfaces

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(Received 29 June 1984; accepted for publication 6 September 1984)

Measurement of sound transmission through a building facade requires determination of the incident sound power. Interpretation of sound pressure level measurements near a facade is, however, complicated by interference between the incident sound waves and those reflected from the facade. Experimental data and a simple mathematical model are used to examine systematic effects associated with reflections from a large flat facade and, subsequently, to investigate deviations from this simple situation. Although the original motivation for the work was the investigation of problems pertinent to measurements of facade sound transmission, many of the results are relevant for other applications involving measurement of noise near a highly reflective surface.

PACS numbers: 43.55.Rg, 43.50.Cb

INTRODUCTION

At a perfectly reflecting surface, the incident and reflected waves have the same amplitude and phase; the resulting pressure doubling gives a sound pressure level (SPL) 6 dB higher than that for the incident wave alone. Near the surface the SPL depends on the phase difference between incident and reflected waves. For a band of noise where phase differences are distributed between 0° and 360° , the average SPL approaches 3 dB above the incident wave SPL, an approximate energy doubling from combining the sound power of incident and reflected waves. The practical problem is to determine the cases in which these limits apply and, if possible, to predict (and correct for) interference effects in intermediate cases.

A simple mathematical model to predict the basic features of the sound field is outlined in Sec. I. Measurements in a hemianechoic room to verify the model are presented in Sec. II, and Sec. III compares measurement and prediction adjacent to large flat building facades. Some effects of facade irregularity are examined in Sec. IV.

I. BASIC PREDICTION MODEL

A simple prediction model was used to demonstrate the potential application of the basic calculation. Despite its simplicity, it gives quite good agreement with experiment. Only a brief outline of the model is presented in Sec. I, but details of the analysis and enhancements of the basic calculation to improve agreement with experiment are given in the Appendix.

The calculations use a plane-wave formulation like that applied by Waterhouse¹ for the analysis of sound fields at the boundaries of a reverberation room. Direct and reflected waves for a specific frequency (f) and angle of incidence (θ) are treated as fully coherent. The normalized, time-averaged squared pressure at a distance x from a perfectly reflecting surface is

$$\langle p^2(f, \theta) \rangle = 1 + \cos [(2\pi fx/c) \cos \theta], \quad (1)$$

where c is the speed of sound and θ is measured relative to the normal to the surface. Contributions from different angles or frequencies are treated as incoherent and are combined by adding their mean-square pressures. Thus for a band of noise incident at angle θ the time-averaged squared pressure is

$$\langle p^2(\theta) \rangle = \int \langle p^2(f, \theta) \rangle W(f) df / \int W(f) df, \quad (2)$$

where $W(f)$ is a weighting function corresponding to the spectral balance of the frequency band (such as 1/3-oct filtered white noise). Two weighting functions were used for the 1/3-oct calculations: either an "ideal" filter with $W(f) = 1$ inside the band and 0 elsewhere, or a function based on the minimum attenuation for a 1/3-oct filter satisfying Class III requirements² of ANSI standard S1.11. The third frequency weighting used in this study was required for comparison with experimental data obtained using a fast Fourier transform (FFT) spectral analyzer. The specific weighting functions and details of the numerical analysis procedure are given in the Appendix.

For analysis of the sound field from a distributed source such as highway traffic, a further averaging over the angle of incidence θ is required. The mean-square pressure at distance x from the surface is given by

$$\langle p^2 \rangle = \int \langle p^2(\theta) \rangle A(\theta) d\theta / \int A(\theta) d\theta, \quad (3)$$

where $A(\theta)$ is the appropriate weighting as a function of angle. For an "ideal line source" (with only attenuation due to geometrical spreading) $A(\theta) = 1$; i.e., incident sound energy per angular interval is constant. For a more realistic line source excess attenuation (due to atmospheric absorption, ground effect, etc.) tends to reduce the contribution from more distant segments of the line source. To obtain an indication of how this might affect the sound field near a surface, calculations were performed with both $A(\theta) = 1$ and $A(\theta) = \cos \theta$ (an arbitrary approximation of excess attenuation effects).

The calculation procedure outlined is properly applicable only for a perfectly reflecting infinite plane. Despite this,

FIG. 1. One-third octave band SPL for normal sound incidence. Experimental data are shown for a 2-kHz band (Δ) and 5-kHz band ($\times$). The solid line is the predicted variation for an ideal filter and the dashed line the prediction for a filter satisfying the minimum class III requirement of ANSI S1.11.²

agreement with experimental observations is rather good. Possible enhancements to provide even better agreement with measured results are discussed in the Appendix.

II. MEASUREMENTS IN AN ANECHOIC ENVIRONMENT

Preliminary measurements were made near a reflecting surface in an otherwise anechoic room. A 7.2- by 4.8-m (12 by 8 ft) wall of 19-mm- $(3/4$ in.) thick plywood was mounted at one side of the anechoic room, and a 6.4-mm- $(1/4$ in.) diam condenser microphone (B&K 4133) mounted through the wall, with its protective cap removed and diaphragm flush with the surface, was used to measure SPL at the surface. The sound source was a 25-mm- $(1$ in.) diam dome loudspeaker located 3 m (118 in.) from the microphone at the same elevation. Sound pressure near the surface was usually measured with a second B&K 4133 microphone at the same elevation; this was aimed vertically to give uniform directivity in the horizontal source-receiver plane. For some of the measurements this microphone was replaced by one of 3.2-mm $(1/8$ in.) diam to assess the effect of microphone size; no significant changes were observed.

A. One-third-oct band measurements at normal incidence

The first two series of measurements used 1/3-oct band-limited white noise as the test signal and an integrating sound level meter (B&K 2218) as the detector system. The input to the sound level meter was switched between the outputs of the two microphone preamplifiers to compare SPL at the two microphone locations for each source-receiver configuration.

For the first series of measurements the source was positioned to give perpendicular incidence at the surface microphone. A second microphone was placed at various positions along a line parallel to the source-surface microphone axis, but offset 50 mm to reduce distortion of the sound field at the surface microphone. The second microphone was centered from 3–100 mm from the reflecting surface. Measure-

FIG. 2. One-third octave band SPL for the 2-kHz band at 100 mm (0.58 wavelength) from the surface as a function of angle of incidence. Experimental data are shown as Δ . The solid and dashed curve are predictions as in Fig. 1.

ments were made for the 1/3-oct bands at 2 and 5 kHz (Fig. 1). The solid line shows the calculated difference in SPL for an ideal 1/3-oct filter; the dashed line shows the corresponding calculation for a filter with the minimum attenuation needed to satisfy class III requirements² of ANSI standard S1.11. As expected, the experimental results generally fall between these limits. Overall agreement of measurement and prediction is good, although data for the 5-kHz band are shifted noticeably from the predicted dependence on distance from the surface. The relation between incident sound power and measured sound pressure changes drastically over the range from 0.1–1 wavelength from the surface, and quite small changes in microphone position can significantly alter the measured 1/3-oct SPL.

B. One-third-oct band measurements versus angle of incidence

This series of measurements used the same conventional 1/3-oct instrumentation, with different microphone and source positioning. The second microphone was placed 100 mm from the surface and the loudspeaker was moved to provide angles of incidence ranging from 0° (normal incidence) to 70° at the surface microphone.

Data for the 1/3-oct band at 2 kHz are presented in Fig. 2; the angle of incidence for the plotted points is the angle for specular reflection to the second microphone. The predicted effects (solid and dashed lines for an ideal and minimal 1/3-oct filter, respectively, as in Fig. 1) agree very well with the experimental data. Similar experimental and predicted results for the 5-kHz band are presented in Fig. 3. As with the normal incidence data in Fig. 1, the experimental data at 5 kHz are not perfectly aligned with the calculated curve.

The interference extrema occur at frequencies determined by the difference between the direct and reflected paths to the second microphone. Changing the angle of incidence gives the same effect as changing the microphone-to-surface distance if the path length difference is the same. For example, the change with angle of incidence from 0° (normal

FIG. 3. One-third octave band SPL for the 5-kHz band at 100 mm (1.44 wavelength) from the surface as a function of angle of incidence. Experimental data are shown as $\times$. The solid and dashed curves are predictions as in Fig. 1.

incidence) to 75° in the 5-kHz data of Fig. 3 is equivalent to moving the microphone from 1.44 to 0.37 wavelength from the surface in the normal incidence case shown in Fig. 1. This complementary feature of incidence angle and microphone-to-surface distance should be considered in any criterion for microphone placement in measurement standards.

C. Alternative measurement technique

A clear impression of the interference effects near a reflecting surface can be obtained more easily by using frequency (rather than source or microphone position) as the independent variable. A two-channel fast Fourier transform (FFT) analyzer (Hewlett-Packard 3582A) was used to measure the response at the two microphones. The experimental results are the rms average of 256 spectra measured in the dual channel spectrum amplitude mode. Thus results for each spectral line should correspond to what would be measured over that time interval by a conventional sound level

FIG. 4. SPL 100 mm from surface relative to SPL at surface for normal incidence. Experimental results obtained with two-channel FFT analyzer as shown as $\bullet$. The dashed curve is the corresponding predicted variation with frequency, as discussed in the text.

meter with a corresponding narrow-band frequency filter. A bandlimited (1–10 kHz) white noise signal was used to drive the loudspeaker, which was 3 m from the surface microphone. The data in Fig. 4 are for normal incidence, with the second microphone 100 mm from the reflecting surface. Interference between direct and reflected waves is clearly evident in the succession of minima and maxima whose amplitudes agree quite well with the dashed curve; this was calculated for the FFT spectral resolution, assuming a perfectly reflecting surface. With increasing frequency, inaccuracy in predicting the frequencies of the interference extrema is evident. This is consistent with the shift noted previously for the 5-kHz band data in Figs. 1 and 3, and might be due to a phase shift on reflection from the untreated plywood surface (not allowed for in the basic calculation procedure).

D. Practical problems in measuring SPL at a surface

For most field measurements it is not practical to install a microphone through a facade, as was done in this study to measure SPL at the surface. The obvious practical compromise is to place the microphone against or very near the surface. As indicated in Figs. 1–3, this gives a result very close to the surface SPL if the microphone center is much less than 0.1 wavelength from the surface. Unfortunately, typical microphones extend beyond this limit for the frequency range of practical interest in sound transmission measurements.

Figure 5 shows the difference, with the sound source at normal incidence, between surface SPL measured with the flush-mounted microphone and that measured with a 25.4-mm (1 in.)-diam microphone touching the surface. The dashed line shows the calculation for expected SPL at the microphone midpoint; a sharp minimum is predicted near 7 kHz. The response of the microphone to the sound pressure distribution over the entire diaphragm limits the measured minimum, but agreement with prediction is good in the range of practical interest up to about 5 kHz. Measurements with smaller microphones centered at the same location should approach the calculated result more closely. The sub-

FIG. 5. SPL measured by a 1-in.-diam condenser microphone touching the surface, relative to surface SPL, for normal incidence. Experimental FFT data are shown as $\bullet$ and the dashed line is the corresponding predicted difference from surface SPL at the microphone midpoint.

FIG. 6. SPL measured by 0.5-in.-diam (●) and 0.25-in.-diam (×) condenser microphones touching the surface, relative to surface SPL, for normal incidence. The dashed and solid lines are the corresponding predicted difference in SPL for the microphone midpoint.

stantial deviations from the predicted curve above 7 kHz are primarily due to diffraction and microphone response characteristics typical of free-field condenser microphones of this size in this frequency range. There are, however, small deviations from predicted behavior even at lower frequencies. Similar deviations are evident in the results presented in Fig. 6 for 12.7-mm (0.5 in.) and 6.3-mm- (0.25 in.) diam microphones touching the surface. These deviations are believed to be due to the perturbation of the sound field at both microphones by diffraction and scattering from the second microphone and its stand; similar effects have been reported elsewhere.^{3,4}

For the frequency range of practical interest (up to 5 kHz) the experimental data are within ~ 1 dB of the predicted results. The data in Figs. 5 and 6 (all for normal incidence) show the worst case, both for differences between measured and predicted performance and for deviation from pressure doubling at the microphone touching the surface. Increasing

FIG. 7. SPL 2 m from a facade relative to surface SPL, for normal incidence. Experimental FFT data are shown as ●; the dashed line is the corresponding predicted difference. The solid curve is the 1/3-oct band difference calculated from the measured FFT results.

the angle of incidence shifts the first interference minimum to higher frequencies or, equivalently, extends the distance from the surface for which pressure doubling is a good approximation. Thus, for example, the results for a 1-in. microphone with sound incident at 60° are similar to those shown in Fig. 6 for normal incidence on a 1/2-in. microphone.

III. MEASUREMENTS NEAR FLAT FACADES

A. Influence of outdoor propagation effects

Results quite similar to those presented in Sec. II may be observed adjacent to building facades (Fig. 7). Surface sound pressure was measured with a 12.7-mm (0.5 in.)-diam condenser microphone (B&K type 4149) touching the surface near the middle of the wall approximately 1.5 m above the ground surface. A loudspeaker system on the ground 25 m from the surface microphone gave a white noise signal at essentially normal incidence. A second microphone of the same type was placed 2 m from the exterior wall, in line with the source. Both microphones were mounted on preamplifiers (B&K type 2619) and pointed vertically. Both had foam windscreens; that on the surface microphone had a slice cut off to permit microphone placement within ~ 1 mm of the surface. The predicted difference in SPL (dashed curve in Fig. 7) was calculated for the path length difference between the direct and reflected rays from the loudspeaker to the second microphone. Reflections from the ground surface were ignored in the calculation.

Location of the experimental maxima and minima was in good agreement with the predicted curves; but the minima were not so pronounced as those in the anechoic room data (Fig. 4), and the maxima differed noticeably from the predicted 0 dB. Measurements with different loudspeaker and microphone positions at several facades gave comparable results; the maxima were typically within ~ 1 dB of the predicted value (much closer on average) and the minima ranged from 2–8 dB above the predicted values.

The most obvious explanation for these deviations from prediction is interference with sound waves reflected from the ground surface. Another factor, which should be checked in outdoor propagation, is the effect of atmospheric turbulence.⁵ The prediction model assumes perfect coherence between direct and reflected waves at any frequency. At the surface microphone the direct and reflected rays should be coherent because path length difference is negligible, but turbulence could reduce coherence between the direct and reflected waves reaching the microphone 2 m from the surface. In frequency ranges where the result of the direct wave and that reflected from the wall is the same at the two locations (i.e., where the phase difference $\simeq 360 \times$ an integer) the correlation between the signals from the two microphones gives a direct measure of correlation between direct and reflected waves at the second microphone. The "coherence amplitude" was measured with the HP3582A FFT analyzer. For anechoic room data (Fig. 4) coherence was ≥ 0.995 near the interference maxima; for data like those in Fig. 7 the coherence was ≥ 0.98 . This reduction in coherence would not significantly affect the results near the maxima, and even at the minima (where interference cancels the coherent components) they should have much less effect than the observed

FIG. 8. Difference in SPL at the facade for microphone locations 2 m apart. Experimental FFT data are shown as ●. The dashed curve is the ideal (0 dB) difference.

deviations from prediction. The deviations are apparently caused by source directionality or differences at different measuring positions in the interference due to ground reflections.

The effect of reflections from the ground surface can be shown more directly by examining the variation in sound pressure level over the wall surface. Figure 8 gives the measured difference in SPL at two microphones 2 m apart, both touching a large flat masonry wall. Changing the microphone or source positions altered the dependence on frequency. Decreasing the microphone separation to 200 mm reduced maximum intermicrophone differences to ~ 0.5 dB. Interchanging microphone positions inverted the measured interchannel differences, showing that these are differences in SPL at the measurement positions, with negligible distortion by instrumentation effects such as microphone response.

FIG. 9. Difference between the "free-field" SPL (beyond a building corner) and the SPL at the building surface. Experimental data for one case (second microphone 2 m beyond corner and surface microphone 1 m from the corner) are shown by ●. The solid curve is the difference between the averages for three positions beyond the corner and three positions on the surface. The dashed line shows the ideal (6 dB) difference expected due to pressure doubling at the surface.

Changing interference between direct and ground-reflected waves might be due to changes in path length difference and/or variations in the complex reflection coefficient of the rather bumpy grass-covered surface between the loudspeaker and the wall. One obvious implication of the results is that several measuring positions are needed for accurate determination of the average sound pressure level at the surface of a building facade.

The data obtained using the FFT analyzer provide extra insight into the relevant physical effects, but for practical applications 1/3-oct results are of primary concern. Fortunately, 1/3-oct spectra can be synthesized readily from the two FFT spectra to obtain the corresponding differences in 1/3-oct band SPL, as shown by the solid curve in Fig. 7. Expressing the results in 1/3-oct bands reduces the apparent interference effects; for the high-frequency bands the difference in SPL approaches 3 dB, as expected, but the smaller bandwidth of the lower bands permits resolution of the interference pattern and substantial deviations from the 3-dB difference.

B. Comparison of surface and incident sound pressure

In addition to the practical problems of measuring the average sound pressure level at the surface, the relation between this average surface SPL and that for the incident wave must be established. Standards for measuring facade sound transmission^{6,7} commonly assume that SPL at building surfaces is 6 dB higher than that for the incident wave. Diffraction and response of the surface to the sound field could introduce deviations from this assumption. To investigate, measurements were made at several positions on the wall surface and beyond the corners of two different buildings. The sound source was on the ground surface 25 m from the corner, in the plane of the second wall surface, to provide essentially normal incidence at the surface microphone and no geometric reflection at the second (free-field) microphone. Results with the surface microphone 1 m from the corner and the second microphone 2 m beyond the corner are given the symbol ● in Fig. 9; corresponding data for the other building may be seen in Fig. 6 of Ref. 8. Significant variation with frequency is evident; this depended strongly on location of the surface and free-field microphones relative to the corner. For nominally identical microphone locations the results at the two buildings exhibited different variations with frequency. The differences in results for the two buildings indicate that systematic effects such as diffraction fringes at the corners do not dominate the observed frequency dependence. Because similar effects were observed far from the corners (as in Fig. 8), it seems reasonable to attribute both to variations in the interference with reflections from the ground surface. The solid curve in Fig. 9 shows the effect of averaging over three microphone locations (0.5, 1, and 2 m from the corner) to determine average and free-field sound pressure levels. This averaging reduces the deviation from the expected 6-dB difference to ~ 1 dB. Combining results from several corners (with different ground effects) and converting to 1/3-oct bands would further reduce the deviations. On average, the assumption of pressure doubling at building surfaces appears to be quite accurate.

FIG. 10. SPL 2 m from building facade relative to surface SPL for 60° incidence. Experimental FFT data are shown by ●; the dashed line is the corresponding predicted difference. The solid line gives the 1/3-oct band results synthesized from the measured FFT data.

C. Variation with angle of incidence

The variation with angle of incidence observed at the building facade showed good agreement with the basic calculation. Figure 10 shows the difference between SPL at the surface and that 2 m from it for an angle of incidence of 60° at the surface microphone. Comparing this with the data in Fig. 7 for normal incidence and the same microphone locations, the increased separation of the interference extrema is obvious. As in Fig. 7, agreement with prediction is generally good, but there are deviations presumably due to ground reflections. The changing frequency dependence gives more resolution of the interference pattern in the relevant 1/3-oct bands with increasing angle of incidence (solid curves in Figs. 7 and 10). It should be emphasized that distance from the surface plays an equivalent role: For normal incidence, a microphone 1 m from the surface would give the same result as that shown in Fig. 10; with increasing angle of incidence even larger deviations from the commonly assumed energy doubling (3 dB below surface SPL) would occur in the lower 1/3-oct bands. For measurements with a moving point source, such as a truck or an airplane, the changing interference pattern (as the source passes) gives a changing relation between the sound power level of the incident wave and the sound pressure level measured near a reflecting surface. A similar problem due to the effect of ground reflections has been discussed by Yamada.⁹

Fortunately, the most common practical problem, noise from road traffic, involves sound incident from a range of angles. Because of the systematic change in interference pattern with angle of incidence, these effects are reduced by averaging over a distribution of sources. Figure 11 shows the predicted and measured differences in SPL for microphones touching and 2 m from a large flat masonry wall facing a major highway. The calculation (dashed line in Fig. 11) assumes a perfectly reflecting surface and an ideal line source, with frequency weighting corresponding to the FFT data. The equivalent curve for 1/3-oct resolution¹⁰ is very similar.

Below 150 Hz the predicted and measured results in Fig. 11 show good agreement, but increasing scatter is evi-

FIG. 11. SPL 2 m from a concrete wall relative to surface SPL; the source is traffic on a nearby road parallel to the facade. Experimental FFT data are shown by ●; the dashed line is the corresponding predicted difference for an "ideal line source" as discussed in the text. The solid curve shows 1/3-oct band results synthesized from the FFT data.

dent at higher frequencies. This is probably due to atmospheric turbulence. The calculation assumes perfect coherence between the direct and reflected waves from each element of the line source; this is obviously not physically realistic for long-distance outdoor propagation. Unfortunately, with sound simultaneously incident from a range of angles there is no straightforward means of measuring the coherence for a single angle of incidence (which is the relevant concern for the prediction model).

The solid curve in Fig. 11 presents 1/3-oct data calculated from the FFT spectra. For the practical frequency range (above 100 Hz) the 1/3-oct results converge, as expected, to approximately 3 dB below the surface sound pressure level. Even for the lowest (100 Hz) band, deviation from the expected value is less than 1 dB. Of course, placing the microphone closer to the surface would shift the interference pattern to higher frequencies, increasing the deviation from energy doubling for the lower 1/3-oct bands.

FIG. 12. SPL 2 m from a wall relative to surface SPL with traffic noise from road parallel to the facade. Experimental FFT data are shown by ●. The dashed and solid lines are the corresponding predicted differences for an "ideal line source" and "modified line source," respectively.

Data for another microphone position 2 m from the wall are presented in Fig. 12. As in Fig. 11, the dashed curve was calculated for an "ideal" line source. The source curve in Fig. 12 was calculated for a modified line source (as discussed in Sec. I), with an arbitrary reduction in the relative contribution from more distant elements of the line source. The experimental data fall between the two prediction curves. This is not a proper test of the modified angular weighting because the stronger interference effects due to reducing the contribution from large angles of incidence are doubtless offset here by the appreciable incoherent component in the signal (indicated by the scatter in the experimental spectrum). The balance between these effects would clearly depend on both the site and atmospheric conditions; for practical purposes the ideal line source calculation provides a reasonable (if slightly conservative) estimate of the typical interference pattern.

Similar trends were evident in 1/3-oct band data obtained by Hall *et al.*,¹⁰ except for an anomalous deviation in the 40-Hz band. The present data (for a very large, featureless, painted masonry facade) show no anomaly around 40 Hz. It is believed that the 40-Hz anomaly and the appreciable scatter from site to site in the previous study¹⁰ were due to reflections from protruding roofs and other facade irregularities, as will be discussed in Sec. IV.

IV. EFFECT OF FACADE IRREGULARITY

The data presented in Sec. III were all obtained adjacent to large flat masonry facades. In practice, measurements are often required at more complex facades where reflection from protruding elements or the low impedance of some surfaces may cause deviations from what would be observed at a uniform, highly reflecting facade. Measurements were made to assess the typical strength and probable cause of such deviations.

A. Recessed doors and windows

The sound pressure level at the surface of recessed doors and windows was compared with that on large adja-

FIG. 13. SPL at a recessed window surface relative to SPL at an adjacent wall surface. Experimental FFT data are shown by ●; the solid curve is the corresponding 1/3-oct band SPL difference synthesized from the measured FFT data.

FIG. 14. Experimental arrangement for controlled simulation of a recessed surface. Both microphones were in contact with the concrete wall. The glass fiber wedge at the left side of the 1 × 1 m plywood frame was added to reduce reflections from the frame to the reference microphone position at the left.

cent wall surfaces of several buildings. A typical experimental result at a window surface is given in Fig. 13; similar data for measurements on a door surface have been published.⁸ There are no obvious differences between the effects at doors and windows. The intermicrophone SPL differences were much greater than those shown in Fig. 8 for two positions on a flat facade. Changing the angle of incidence or the microphone position on the recessed surface strongly altered the observed frequency dependence. Averaging over 1/3-oct bands (solid curve in Fig. 13) reduced the apparent frequency dependence, but significant effects were still evident in the low-frequency bands.

Because of uncertainty about the impedance of their surfaces, the local variation in SPL adjacent to doors or windows might be due to either resonant response of the surface to the sound field or reflection and diffraction from the surrounding frame.

B. Controlled simulation of a recessed surface

To investigate the cause of the effect observed at doors and windows, another series of measurements was made, after adding a rectangular frame to an otherwise featureless masonry facade (Fig. 14). This frame was made of 38-mm (1.5 in.)-thick plywood and had interior dimensions 1 × 1 × 0.2 m (40 × 40 × 8 in.). A wedge of glass fiber was added at one side to reduce reflections towards the reference position on the wall surface near the frame. The loudspeaker source was placed on the ground surface 25 m from the frame midpoint to given an angle of incidence of 0°, 30°, 45°, or 60° at the frame.

Figure 15 shows the effect of adding the frame for a microphone touching the wall surface at the frame's mid-

FIG. 15. Change in SPL at the wall surface due to added surrounding plywood frame. The dashed line shows the FFT data for normal incidence and the solid line the FFT data for 60° incidence; both were measured at the box midpoint.

point. The average effect of the frame at the reference position and the average difference between the two measurement positions without the frame were determined from repeated measurements with small alterations in microphone, source, and frame positions for each angle of incidence. Applying these corrections to the intermicrophone difference for positions, as illustrated in Fig. 14, gave the nominal change at the second microphone due to addition of the surrounding frame. The two sets of data for 0° and 60° incidence in Fig. 15 illustrate the trend to stronger frequency dependence with increasing angle of incidence. For any frequency, both the amplitude and the sign of the change in SPL depend on the angle of incidence. For a fixed angle of incidence, similar changes in SPL difference were observed between different positions on the wall surface within the frame area.

It seems safe to reject the possibility that addition of the frame significantly alters the response of the masonry wall surface. To investigate the possible effect of a low surface impedance, however, measurements were made with a 3-

FIG. 16. Change in 1/3-oct band SPL (synthesized from FFT data) at the wall surface due to added surrounding plywood frame. The solid curve is the average for eight positions on the surface inside the frame. The dashed curve is for one of these positions (165 mm from bottom, 380 mm from left).

mm (1/8 in.)-thick Plexiglas panel mounted inside the frame approximately 20 mm (3/4 in.) from the masonry surface. The results were almost identical to those shown in Fig. 15; the amplitudes of the extrema matched within ~ 1 dB and their frequencies were unchanged. These minimal changes and the similarity between the results in Figs. 13 and 15 suggest that the strong variation in SPL observed at the surface of recessed doors and windows is primarily due to interference of waves reflected from the surrounding frame.

Because the sound pressure level at the surface is modified by this effect, sound transmission through a window may depend on the shape and depth of the frame. The curves in Fig. 16 show the change in sound pressure level at the surface due to the added frame. For most bands the SPL is reduced even in the solid curve (an average for eight positions, most on symmetry axes) and the reduction is more pronounced in the dashed curve (which was for a low symmetry position). The number of measurement positions and angles of incidence were insufficient for quantitative assessment, but the data suggest a reduction in SPL at the surface (and hence an increase in effective sound transmission loss). This seems to be a free-field equivalent of the "niche effect" reported in reverberant room sound transmission studies.

The practical problem is to assess whether use of sound pressure levels measured at a recessed surface will significantly distort the resulting 1/3-oct band sound transmission results. The solid curve in Fig. 16 shows the effect of the frame on the sound pressure level average for eight positions at the wall surface within the frame. If simple pressure doubling were assumed, this effect would significantly distort the apparent spectrum of the incident wave. The data in Fig. 16 are for 60° incidence; for a distributed source the angular averaging should diminish the effect. The scatter evident in previously published data¹⁰ for SPL at window surfaces exposed to traffic noise suggests, however, that angular averaging does not reduce the effect to insignificance. Despite their common acceptance,^{6,7,11} it seems prudent to avoid the use of sound pressure level measurements at a recessed surface to determine the incident sound power. Where no alternative is feasible, the average for many positions on the surface should be used.

V. SUMMARY

The basic problem examined in this study is the accurate determination of sound power incident on a facade from measurements of the sound pressure level near the surface. Owing to changing interference between direct sound waves and those reflected from the ground surface, the average of measurements at numerous positions distributed across the surface is required for an accurate measurement of incident sound power.

In addition to averaging out perturbations due to ground reflections, one must make allowance for the interference effects of reflections from the building surface. To simplify measurement procedures it is clearly desirable to position the outdoor microphone(s) so that "pressure doubling" (SPL 6 dB higher than that for the incident wave) or "energy doubling" (SPL 3 dB higher than that for the incident wave) may be assumed for the frequency range of inter-

est. Existing standards for measuring sound transmission through facades^{6,7} roughly restrict themselves to these conditions. In many practical measurement situations the 3- and 6-dB approximations are not appropriate and explicit allowance for the interference effects is required in determining incident sound power from measured sound pressure levels. Fortunately, the necessary corrections can be calculated quite accurately with a simple prediction model.

A good approximation to pressure doubling is observed, on average, very close to flat building surfaces. As a rough guide, the deviation from pressure doubling should be negligible if the microphone does not extend beyond ~ 0.05 wavelength from the surface. For the frequency range of common interest (up to ~ 5 kHz) the effects will not be negligible except for small microphones (diameter under 13 mm) essentially touching the surface. The appropriate corrections depend on microphone position and angle(s) of incidence, and can be calculated as shown in Figs. 5 and 6.

At recessed surfaces such as doors and windows, strong interference and/or diffraction effects are common. Averaging over many positions on the recessed surface reduces the deviations from pressure doubling, but a systematic effect (possibly analogous to the "niche effect" in sound transmission between reverberant rooms) seems to be involved.

The assumption of energy doubling at 2 m from a building surface is a reasonable approximation for a distributed source, such as road traffic, for 1/3-oct bands above 100 Hz. The low-frequency limit is inversely proportional to distance from the surface. For a point source, interference between the incident wave and that reflected from the surface significantly alters the relation between incident sound power and measured sound pressure level. The effects are most pronounced for the low-frequency 1/3-oct bands, and depend on both microphone position and angle of incidence. These effects can be calculated (and hence corrected for) with reasonable accuracy.

ACKNOWLEDGMENT

This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

$$W(f) = 1, \text{ near the nominal frequency, } (|f - f_0| \leq 0.0136f_0)$$

$$= \sin \left[\frac{\pi}{2} \left(1 + \frac{|f - f_0| - 0.0136f_0}{0.002f_0} \right) \right], \quad 0.0136f_0 < |f - f_0| \leq 0.0156f_0$$

$$= 0, \text{ outside the passband, } (|f - f_0| > 0.0156f_0),$$

(A2)

where f_0 is the nominal frequency of the spectral line. The numerical evaluation of the integrals in Eq. (2) used this expression for $W(f)$ at 80 frequencies at intervals of 1/2500 of the spectrum bandwidth.

B. Calculations for distributed sources

For prediction of the sound field generated by distributed sources such as road traffic a further averaging over the angle of incidence was performed, with the angular weighting functions $A(\theta)$ given in Sec. I. The integrals in Eq. (3) were

APPENDIX: DETAILS OF THE PREDICTION MODEL

The general features of the mathematical model for predicting sound pressure level near a reflecting surface are outlined in Sec. I. This Appendix gives details of applications of the basic prediction model and presents enhancements to the model to allow for the finite impedance of real facades.

A. Results for a band of noise

For a band of noise, the expression for the mean-square sound pressure level in Eq. (2) was evaluated numerically from the weighted contributions for a series of frequencies distributed across the band. The 1/3-oct band calculations used 151 frequencies at intervals of 1/200 of the center frequency. Two weighting functions were used to approximate the limits for typical 1/3-oct filters: The "ideal" weighting function is $W(f) = 1$ inside the passband and 0 elsewhere; the second limit was the minimum class III attenuation requirement² of ANSI standard S1.11. For this

$$W(f) = \left[\frac{8}{13} + 2500 \left(\frac{f}{f_m} - \frac{f_m}{f} \right)^6 \right]^{-1}, \quad (\text{A1})$$

where f_m is the band midfrequency. Where the expression in Eq. (A1) exceeds unity in the passband, the limit $W(f) = 1$ was used.

The third frequency weighting used in this study was required for comparison with measurements using a Hewlett-Packard HP3582A FFT analyzer. The experimental data were obtained in the dual channel spectrum amplitude mode from the rms average of 256 spectra. Thus the results for each spectral line should correspond to the rms sound pressure level that would be measured by a sound level meter with an appropriate frequency band filter. The "flat top passband shape" was used for the measurements; this has a time-domain window with a 10% cosine taper at its limits, giving an effective bandwidth for each spectral line of 0.029 of the spectrum bandwidth. The weighting function used in the calculations to provide equivalent frequency resolution was

evaluated numerically using an angular increment of 1° for angles from 0.5° to 89.5° to obtain the curves in Figs. 11 and 12. Similar results for 1/3-oct frequency bands were presented in an earlier paper.¹⁰

C. Extension to include facade absorption

Although real facades are highly reflective, they do absorb sound energy, especially at low frequencies. For a locally reacting surface with a real impedance (i.e., no phase shift

on reflection) the effect of energy transfer into the surface can be readily included, replacing Eq. (1) with the expression

$$\langle \bar{p}^2(f, \theta) \rangle = \frac{1}{2} \{ 1 + R^2 + 2R \cos[(2\pi fx/c) \cos \theta] \}, \quad (\text{A3})$$

where R is the reflection coefficient related to the specific admittance β of the surface by

$$R = (\cos \theta - \beta) / (\cos \theta + \beta). \quad (\text{A4})$$

The specific admittance β may be related to the normal incidence absorption coefficient α_0 and thus to the random incidence absorption coefficient α .¹² For an exterior facade, absorption coefficients exceeding 0.2 are unlikely. Calculations were made for a quite absorptive surface (α from 0.04 above 1 kHz to 0.2 at frequencies below 160 Hz) and some results have already been presented.¹⁰ Quantitative details are not of great significance because of probable physical deviations from the assumptions of real surface impedance and local reaction. The qualitative features are, however, worth noting: Inclusion of surface absorption should affect measured sound pressure levels near a facade by less than 0.5 dB, with substantially smaller effects for the difference between surface SPL and that near the surface (the measurement situation in this study).

In cases where the impedance of a surface is known, the modified expression for $\langle \bar{p}^2(f, \theta) \rangle$ could be used in the calculation procedure outlined in Sec. I. Allowance for a known phase shift ϕ , on reflection, by adding ϕ to the argument $2\pi fx \cos(\theta)/c$ is another possible refinement. In principle, the surface impedance, and hence the relevant values of R and θ , can be measured.^{9,13} These enhancements of the basic calculation were not applied to this paper because the information on surface impedance would not be available in com-

mon practice and the basic calculation seems to give adequate accuracy.

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