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Full-scale measurements for noise transmission in tunnels

K. M. Li[a)] and K. K. Iu
Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong

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In many previous studies, energy-based methods are used to predict the attenuation of sound in long tunnels. However, these models do not address the interference effects of the sound fields generated by all image sources. A numerical model has been developed, in which the total sound field is computed by summing contributions from all image sources coherently. This numerical model also incorporates a correction term for calculating the atmospheric absorption of sound in air. To validate the numerical models in practical situations, two road traffic tunnels have been chosen for extensive measurements. The levels of the transmitted noise have been recorded in one-third octave band frequencies at various separations up to a maximum of 400 m. The predictions using the coherent model agree reasonably well with the measured data at all frequencies. The agreements between the field data and the theoretical predictions using the energy-based model are tolerable at high frequency, but less so at low frequency. In most cases, the predictions of the coherent model give the best results, with an accuracy to within 3 dB. On the other hand, the energy-based models are not able to predict the peaks and dips across the frequency spectra, the variance with the measurement results being up to 7 dB at low-frequency bands. © *2005 Acoustical Society of America.* [DOI: 10.1121/1.1859251]

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I. INTRODUCTION

The current study is motivated by the need for a better understanding of sound propagation in tunnels. This can provide useful information for improving the acoustic environments of road traffic tunnels. Despite considerable improvements in computer performance and the accelerating development of many numerical achemes, full-scale measurements are still popular for studying sound fields in long ducts, such as corridors and tunnels. The present work is a continuation of our earlier study[1] that investigates the theoretical models for predicting the propagation of sound in long enclosures. A comprehensive literature review of the problem can be found in Ref. 1 and its cited references. In this paper, we wish to show the robustness of the complex image source model[2] (also known as the coherent model) for the prediction of sound fields in long ducts with geometrically reflecting boundaries. Extensive full-scale field measurements in two tunnels for road traffic are conducted and to the results compared with numerical predictions. We endeavor to study the importance of the interference effects caused by the direct and reflected waves for the accurate prediction of sound fields in long tunnels. To demonstrate that the coherent model is valid for a long propagation distance, measurements are taken in the tunnels up to a distance of several hundred meters from the source.

The problems are simplified, somewhat, by modeling the propagation of sound in long tunnels as an analogous situation to the determination of sound fields in a long enclosure bounded by two parallel vertical inwalls of infinite extent and two parallel horizontal planes. Although impedance boundary conditions can be implemented onto all vertical and horizontal planes in our numerical model, the analyses here are restricted to perfectly reflecting walls, ceiling, and ground. This simplification is justifiable because the boundary walls of most tunnels are constructed with acoustically hard materials. Two different tunnels, which are normally used for road traffic, are chosen for field measurements in the present study. The experimental results will be used to compare with different numerical models.

The structure of the paper is as follows. In Sec. II we outline the numerical models used in the present study. The effect of atmospheric absorption of sound has been incorporated in the numerical analyzes. The issue on the number of image sources required for the calculation has also been addressed. In Sec. III, we describe experimental studies for noise transmitted in two tunnels. Experimental results are compared with numerical predictions. Finally, the outcomes of the current study are summarized in Sec. IV.

II. NUMERICAL SIMULATIONS

A. The effect of atmospheric absorption of sound in air on the prediction models

The attenuation of sound due to atmospheric absorption is well known and has been studied for decades.[3] A practical method for calculating the attenuation of sound in air is to multiply an exponential term, $\exp(-ad)$, to account for the reduction of sound energy caused by air absorption. This term is also known as the air absorption factor where a is the attenuation of sound in air and d is the distance of the receiver from the source.

Recently, the Acoustical Society of America has published an American National Standard, ANSI S1.26-1995,[4] to provide a means of calculating the atmospheric attenuation of sound in air from any source, moving or stationary, for a wide range of meteorological conditions. In view of a recent

[a)]Electronic mail: mmkmli@polyu.edu.hk

study,[1] the modified expressions for sound propagation in a long tunnel with geometrically reflecting boundaries may be written as

$$P(N)=\frac{1}{4\pi}\sum_N \frac{\exp(ik'd_N)}{d_N}, \tag{1}$$

where $k'(=k+0.115ia)$ is the modified wave number and a is the coefficient of sound attenuation that has units of $\mathrm{dB\,m^{-1}}$. The real part of the modified wave number, k $(=\omega/c)$, is the ratio of the angular frequency of the source to the speed of sound in air. The imaginary part of the modified wave number accounts for the attenuation of sound in air due to the effect of atmospheric absorption. The total sound field is obtained by summing contributions from all image sources to the receiver with d_N as the distance from the Nth image source to the receiver. The term N may also be regarded as the order reflections from the boundary surfaces. We refer to the formulation given in Eq. (1) as the coherent model. It is noteworthy that the use of Eq. (1) implies that specularly reflections occur at the boundaries of the enclosure. This assumption is justifiable because there are usually few diffusely reflecting surfaces employed in the construction of road traffic tunnels. The use of a model for diffuse reflection of boundary surfaces will not be considered in the present study.

The third formulation used in our study is a simple energy-based model developed by the Acoustical Society of Japan published.[1,5] The formula, which may be found in Eq. (9) of Ref. 1, is referred to as the ASJ model. The attenuation of sound due to atmospheric absorption can easily be incorporated in the ASJ model by multiplying the existing formula with the same exponential factor, $\exp(-ad)$, as discussed earlier in the incoherent model.

B. Noise reduction

The levels of sound energy are usually calculated in the incoherent and ASJ models, but the sound pressure levels are predicted by the coherent model. For ease of comparison of different theoretical models and experimental data, we use a term known as the noise reduction (NR), which is defined as the ratio of the total sound field, $P(N)$, measured at various receiver locations to the total field, $P_{10}(N)$, measured at 10 m in front of the source:

$$\mathrm{NR}=20\log[P(N)/P_{10}(N)]. \tag{2}$$

For the coherent model, the total sound pressure levels can be calculated from Eq. (1). On the other hand, the sound energy is usually used in the incoherent and ASJ models. We may modify Eq. (2) to obtain the corresponding noise reduction spectrum as follows:

$$\mathrm{NR}=10\log(I/I_{10}), \tag{3}$$

where I is the total sound energy at various receiver locations and I_{10} is the total sound energy at 10 m from the source. We note that 10 m is chosen as a reference point instead of 1 or 5 m, as used in other studies.[1,6,7] The choice of 10 m ensures that all measurements are conducted outside a hydrodynamic near-field region[8] for a frequency range down to 50 Hz of which the wavelength is 6.8 m. Consequently, the loudspeaker used in our experimental studies can be assumed to be a point source.

C. Number of image sources

The use of ray models to compute the sound field requires the summation of a series of infinite terms. Each "virtual" image source is represented by a term from the series. The contributions of the higher-order image sources, which become weaker in strength when they are located farther apart from the receiver, can be neglected. As a result, only a finite number of image sources contribute significantly to the total sound pressure levels. Dance and Shield[9] described a computer-based image-source model for the prediction of sound distribution in a nondiffuse fitted enclosed space, such as a factory. In their study, the number of "allowable" reflections was determined by using a percentage of energy discontinuity. The percentage is set at a level such that the contribution from a given image source is negligibly small relative to the overall sound level. The relationship between the order of reflection, N, and the energy discontinuity percentage, E_p, is defined by

$$N=\frac{\ln(1-E_p/100)}{\ln(1-\alpha)-al}, \tag{4}$$

where α is the average absorption coefficient of the boundaries, a is the absorption attenuation of air, and l is the mean pathlength from the image sources to the receiver. A typical value of E_p, which allows accurate predictions of the sound field in a range of enclosed spaces, lies between 90% and 99%.[10] Obviously, a smaller value E_p leads to a shorter computing time for ray tracing models because the allowable reflection order, N, is smaller.

When the coherent model is used, we anticipate that a finite number of terms are required in the prediction of the sound field in long enclosures. However, Eq. (4) cannot be used for determining the number of the required terms in the ray series. This is because the coherent model is not an energy-based scheme. In our study, the relative error at the lowest one-third octave band of interest in the total sound field is used to determine the number of required reflections. Here, we define the relative error in total sound field, ΔP, by

$$\Delta P=\left|\frac{P(m+n+2)-P(m+n)}{P(m+n)}\right|, \tag{5}$$

where $P(N)$ given in Eq. (1). It is the total sound field at a particular receiver location due to an image source with N as the order of reflection from the boundary surfaces. The order of reflection can be split into m and n where they are the respective orders of reflections at the vertical and horizontal boundaries. The error in truncating the ray series to Nth order of reflections is bounded by ΔP if N is sufficiently large. The smaller the relative error, the more the terms (i.e., more computational time) are required in the ray series given in Eq. (1).

Figures 1 and 2 show the predicted relative errors for the propagation of sound in tunnels with different conditions. In Fig. 1, we display the numerical simulations for a tunnel that

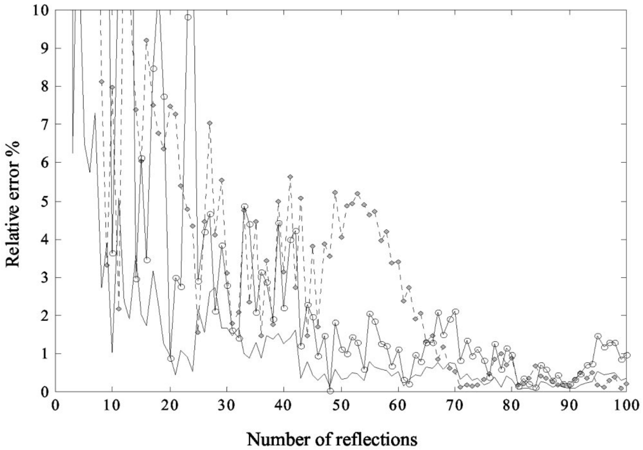

FIG. 1. Comparisons of predicted relative errors versus numbers of reflections at 50 Hz for sound propagation in a realistic tunnel with a cross-sectional area of 12.5 m×5.8 m. Three source/receiver separations are shown. (Dashed line with diamonds: 400 m; solid line with diamonds: 50 m; solid line: 10 m.)

has a rectangular cross-section of 12.5 m×5.8 m. Predictions of the relative error, ΔP, is calculated for a receiver locating at different horizontal distances of 10, 50, and 400 m from the source. In the simulations, the source and receiver are situated at 0.9 and 1.3 m above the ground, respectively. Both the source and receiver are placed at a distance of 2.65 m from one of the vertical walls. Figure 1(a) shows that the direct distance between the source and receiver affects the required order of reflection, i.e., the number of term in the ray series. More image sources are generally required for greater separations between the source and receiver separation.

Next, we show that the size of the tunnel also affects the number of terms required for the ray series. This can be achieved by comparing ΔP for two tunnels with different cross-sectional areas. The first tunnel (Western Cross Harbor Tunnel) has a cross-sectional area of 12.5 m×5.8 m, which has the same dimension as the tunnel used in Fig. 1. The second tunnel (Tai Lam Tunnel), which has a dimension of 14.2 m×6.0 m, is larger than Western Cross Harbor Tunnel. The choice of dimensions used in numerical simulations reflects the actual sizes of the two tunnels employed for field measurements. More details about the tunnels will be described in Sec. III.

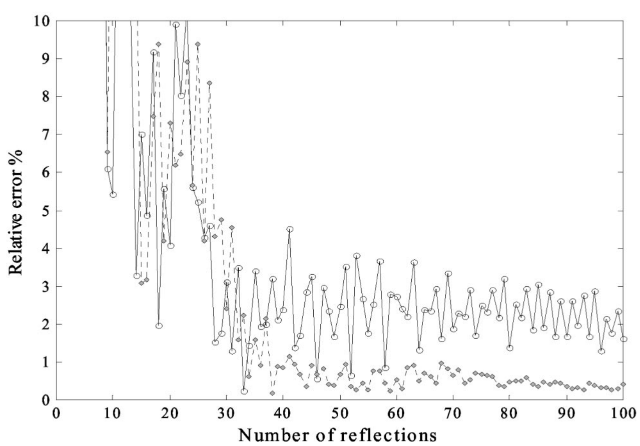

FIG. 2. Comparisons of predicted relative errors versus numbers of reflections at 50 Hz for sound propagation in two realistic tunnels with the source/receiver separation of 200 m. Two cross-sectional areas of the tunnel are shown. (Solid line with diamonds: 12.5 m×5.8 m; dashed line with diamonds: 14.2 m×6.0 m.)

In the numerical simulations, the source is placed at the centerline and at 1 m above the ground in Tai Lam Tunnel. The receiver, which is located at a horizontal distance of 200 m from the source, is placed at an offset position of 3.5 m from one of the vertical wall and at 2.33 m above the ground. For Western Cross Harbor Tunnel, the source is placed at 6.25 m from one of the vertical walls and 0.9 m above the ground. The receiver is placed at 2.65 m from the same vertical wall and at 2.38 m above the ground. Again, the separation between the source and receiver is set at 200 m for Western Cross Harbor Tunnel in the numerical simulations. Figure 2 displays the predicted relative errors versus the orders of reflection for the tunnels with different dimensions. To achieve a comparable relative error in predicting the total sound field, more terms are required for a tunnel with a smaller cross-sectional area. This conclusion agrees with one of the finding in an earlier study for the sound propagation in a narrow city street[6] where more higher-order rays are required for a narrower street.

In the current study, the 50 Hz frequency band is used as the basis to determine the required terms needed in Eq. (1). This is because 50 Hz is the lowest frequency considered in the present study. We find that use of a maximum of 60 reflections from the tunnel walls is sufficiently accurate for the geometrical configuration used in our experimental studies. Generally speaking, fewer terms are required for a source with higher frequencies and for shorter separations between the source and receiver. Although it is possible to optimize the number of terms required in the ray series, no attempt has been made in the numerical simulations shown in this paper. Setting N equal to 60 is adequate to ensure that the resulting ΔP is less than 5% in all calculations.

III. FIELD MEASUREMENTS IN TWO TUNNELS

In a recent study,[1] we have demonstrated that predictions by the coherent model agree well with the measurement data in a scale model experiment. To further validate the coherent model, measurements were conducted at nighttime in two realistic long tunnels, namely Tai Lam Tunnel and Western Harbor Crossing Tunnel in Hong Kong. These tunnels were designed for use by automobiles but closed for general maintenance purposes in the nighttime. Hence, it was a relatively ‘‘quiet’’ environment with a typical background noise level of 60 dB(A) because of the lack of traffic flow during the measurement period. However, occasional noise was generated as a result of maintenance activities.

When conducting the measurements at Tai Lam Tunnel, a subwoofer, the Tannoy B475, was chosen as the noise source. This generates a high definition sound at low and ultra-low frequencies. The frequency response was ± 3 dB in the range from 28 to 240 Hz. While the measurements in Western Harbor Crossing Tunnel are intended to extend to high-frequency regions, a general-purpose speaker, the Tannoy T300, was chosen as the noise source. The Tannoy T300

TABLE I. Absorption coefficients of the tunnel boundaries at 1/3-octave bands.

Frequency (Hz)	50	63	80	100	125	160	200	250
Absorption coefficient	0.015	0.018	0.02	0.022	0.025	0.027	0.029	0.03
	315	400	500	630	800	1 k	1.25 k	1.6 k
	0.032	0.034	0.035	0.037	0.039	0.04	0.044	0.047
	2 k	2.5 k	3.15 k	4 k	5 k	6.3 k	8 k	
	0.05	0.057	0.063	0.07	0.075	0.08	0.09	

comprises one 12 in. dual concentric driver, in which the low-frequency and high-frequency sources were coincidentally aligned to a point source, resulting in a smooth uniform response (± 3 dB) over a wide frequency range from 55 to 22 kHz.

As the wall surfaces along the length of the tunnels were made of concrete, we assume that all boundaries have the same absorption coefficient in the predictions based on the incoherent model. See Table I for the list of the absorption coefficients at each octave band used by Yang and Shield.[10] In predictions according to the ASJ model, Takagi *et al.*[11] have selected an absorption parameter of a value 0.04 for tunnels with concrete wall surfaces. This value is used in our study of the sound propagation in the two tunnels mentioned above.

Both tunnels were built for the use of automobiles. To minimize the influence of background noise, the measurements were taken in the nighttime with a loudspeaker generating high levels of random noise. A precision type sound level meter was used as a signal receiver to measure sound pressure levels in one-third octave bands. In the following sections, we shall show comparisons of the theoretical predictions with experimental measurements.

To facilitate the comparison the theoretical predictions with field measurements, each one-third band is divided into a number of smaller sub-bands of a constant bandwidth. The total sound field is then computed by summing the noise levels of all sub-bands. Since the number of predicted data for each one-third octave band increases with the increasing center frequency because the one-third octave bands are spaced logarithmically. Consequently, the computational effort increases with the increase of the octave-band center frequencies. To reduce the computational time without affecting the accuracy of predictions, the sub-bands are also spaced logarithmically. A preliminary study suggests that use of the logarithmic sub-bands is sufficient for the present numerical analyses.

A. Measurements in Tai Lam Tunnel

Tai Lam Tunnel was 3.7 km long with a rectangular cross-section of a nominal width and height of 14.2 and 6.0 m, respectively. The two sides of the tunnel walls were furnished with smooth concrete panels that were slightly curve for decorative purposes. These vertical walls were assumed to be reflective flat surfaces. The ground was made of concrete with raised walkways formed adjacent to the vertical walls. A slightly curved ceiling made of concrete slab was regarded as a reflective flat surface in parallel with the ground. The lighting equipment and signal boxes were hung from the ceiling of the tunnel. It is remarkable that the boundaries of the tunnel, i.e., the two vertical walls, the ground and the ceiling are considered to form a long rectangular enclosure in our prediction model. As shown in the following comparisons, this simplification does not cause significant errors in predicting the overall noise levels in the tunnel.

The experiments were conducted at the location such that the tunnel exits at either end do not have significant effects on the measurements. A Tannoy Superdual B475 loudspeaker with external dimensions of 0.55 m$\times$0.58 m high was used as a sound source generating white noise in the field measurements. The sound source was located 1 m above the concrete ground and either 3.5 or 7.1 m from one of the vertical walls. These source locations were chosen to simulate the approximate locations of ground-based sources, such as engine noise, emitted from heavy vehicles or elevated noise sources, such as jet fans, installed under the ceiling of the tunnel. Measurements of sound pressure levels in one-third octave bands were recorded using an Ono Sokki Precision Sound Level Meter type LA-5110 at various receiver locations from 10 to 200 m. The receivers were located at the centerline of the tunnel and on the side at 3.5 m from one of the vertical walls. These two locations are referred to as the centerline and offset line, respectively, in this section. The height of the receiver was set at 1.25 and 2.33 m above the ground. They are referred to as the low and high positions, respectively.

In the first set of measurements, the source was located at the centerline, 7.1 m from one of the vertical walls and 1 m above the concrete ground. To obtain the values of noise reduction (NR), as defined above, the sound pressure level measured at a receiver location at a horizontal distance of 10 m in front of the source and at a height 1.25 m above the ground was used as the reference. This receiver location was referred to as the reference point.

Due to the interference effect of the source and its images, the sound levels at octave bands vary considerably, even when the receivers were located close to the source. Figure 3 shows the experimental results of a frequency spectrum for the octave bands from 50 to 500 Hz. A typical geometry was used in the measurements with a receiver located at a horizontal distance of 10 m from the source. The measurements were taken at the same vertical plane as the reference point, but the receiver was moved from the reference point to the high position at the offset line. As illustrated, the coherent model can be used to predict the interference dips at the low-frequency region considerably well, while the predictions according to the incoherent and ASJ models are rather insensitive to the change of receiver loca-

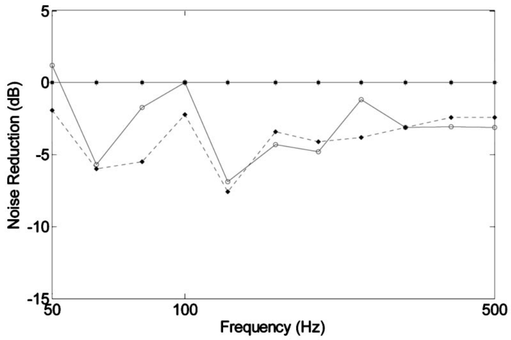

FIG. 3. A comparison of noise reduction spectra among the predictions by the coherent model, incoherent model, ASJ model, and measurements in Tai Lam Tunnel. The source and receiver were placed, respectively, at 1 and 2.33 m above the ground and at respective distances of 7.1 and 10.7 m from one side of the tunnel wall. They were separated by a horizontal distance of 10 m. The predictions according to the incoherent and ASJ models coincide at all frequencies. (Solid line with open circles: Measured results; dashed line with open circle: predictions according to the coherent model; solid line with crosses: predictions according to the incoherent model; dot–dashed line with dark circles: predictions according to the ASJ model.)

tions. The comparison shows that the discrepancy between the measurement result and the prediction by the incoherent and ASJ models can be up to 7 dB at 125 Hz. On the other hand, the variation in the noise reduction (NR) gradually arrives at a steady level of about −3 dB when the octave-band frequency exceeds 315 Hz. The incoherent and ASJ models predict that there is no noise reduction for sound transmitted over a source/receiver separation of 10 m.

To demonstrate the usefulness of the coherent model in the prediction of sound propagation in a long-range situation, we move the receiver farther from the source. We show in Fig. 4 only the results for the measurements at a horizontal distance of 150 m from the source. Again the spectrum frequency is shown with the octave bands varying from 50 to 500 Hz. In this set of measurements, the source was located at the centerline and the receiver at the high position of the offset line. The figure illustrates that the coherent model can be used to predict the fluctuations of noise reduction across the frequency spectrum with accuracy. The incoherent and ASJ models are less accurate prediction schemes for the source frequency below 200 Hz. At the frequency range of interest from 50 to 500 Hz, the ASJ model generally underestimates the sound attenuations along the tunnel.

In the next set of measurements, the source was set at 1 m above the ground and placed either at the centerline or offset at 3.5 m from one of the vertical walls. Noise measurements were conducted along the tunnel from a horizontal distance of 10 to 200 m at the frequency range from 50 to 500 Hz. Two typical sets of data are selected for presentation. In Fig. 5, the receiver was placed at the low position at the offset line with the octave-band frequency of the source at 160 Hz. On the other hand, in Fig. 6, the receiver was placed at the high position at the centerline with the octave band frequency at 315 Hz. These two plots display typical results of the predicted noise reduction by various models with the measured noise reduction plotted against the horizontal distance from the source. These two figures show that higher sound attenuation along the tunnel was achieved when the receiver was located at the low position at the offset line. We also note that there was no appreciable sound attenuation at the receiver locations between 20 and 50 m from the source. Generally speaking, the coherent model gives a more accurate prediction in all source/receiver configurations. As shown in both figures, the predictions according to the coherent model agree to within 3 dB of the experimental measurements. However, there are noticeable discrepancies between the measurement results and predictions according to the incoherent and ASJ models. The differences between the ASJ model and the measurements can

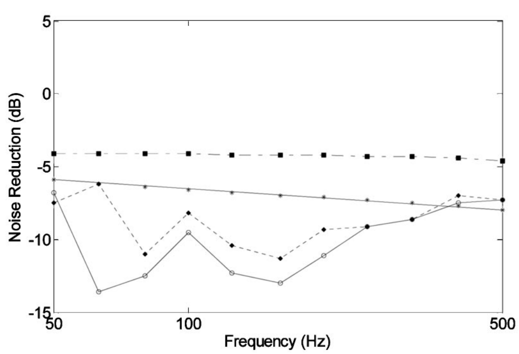

FIG. 4. The same as Fig. 3, except that the source and receiver were separated by a horizontal distance of 150 m.

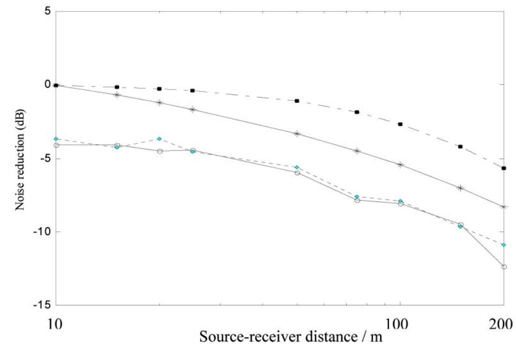

FIG. 5. A comparison of sound attenuation at different source/receiver separations along Tai Lam Tunnel with the noise source located 1 m above the ground and 7.1 m from the tunnel wall. Measurements were conducted for the source frequency of 160 Hz and the receiver locating at the offset line along the tunnel and 1.25 m above ground. The keys for the lines show in the figure are the same as in Fig. 3.

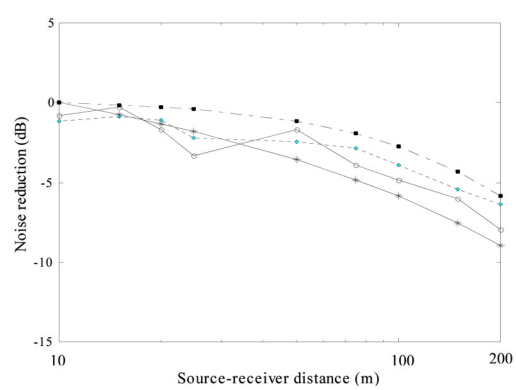

FIG. 6. The same as Fig. 5, except that the source frequency was 315 Hz and the receiver was located at the centerline along the tunnel and at 2.33 aboveground.

be as high as 7 dB. For the source located at the offset position and the receiver located at other distances, comparisons of the experimental data with theoretical predictions have rather similar results. These results are not shown here for brevity.

The usefulness of using the coherent model, i.e., considering the interference, in predicting sound propagation at low frequencies, is generally expected. However, it is of interest to determine the critical frequency where the incoherent models should not be used. The critical frequency may be determined by considering the pathlength difference of the direct ray and the reflected ray of the first order. Suppose that the cross-sectional area of the tunnel is A and the horizontal distance between the source and receiver is L. Then, the typical length scale of the tunnel with a rectangular cross-section is $\sqrt{A}$. The paths of the direct and the reflected ray of the first order have the respective length scales of $\sqrt{L^2+A}$ and $\sqrt{L^2+2A}$. Hence, the pathlength difference has an approximate order of $AL/2(L^2+A)$ which is derived by assuming $D \gg 0$. The effect of interference between the contributory rays is significant if the wavelength λ of the transmitted sound is much less than the pathlength difference, i.e., $\lambda \ll AL/2(L^2+A)$. The critical frequency is then determined by

$$f_c \sim 2c(L^2+A)/AL, \tag{6}$$

where c is the speed of sound in air. The incoherent model should be adequate in predicting the average levels of the transmitted noise if the source has a frequency much greater than the critical frequency.

We remark that the frequency used in the measurements at Tai Lam Tunnel was not high enough to allow an assessment of the critical frequency and source/receiver separation in which the incoherent model may be used to predict the average level of the transmitted noise. This issue will be addressed in the next section.

B. Measurements in Western Harbor Crossing Tunnel

Western Harbor Crossing Tunnel was a 2 km three-lane road tunnel in Victoria Harbor of Hong Kong. This tunnel, which has a rectangular cross-section of a nominal width of 12.5 m and a height of 5.8 m, shares a similar design to the Tai Lam Tunnel described earlier. The tunnel walls and ground were made of concrete with flat and smooth surfaces. Raised walkways adjacent to the vertical walls and other scattering surfaces hung from the reflective ceiling were found. To obtain a full spectrum of measurement results from 50 to 8 kHz, the Tannoy loudspeaker model T300 with external dimensions of 0.37 m×0.59 m in height was used as a sound source generating pink noise. The sound source was located at 0.9 m above the concrete ground and at either 2.65 or 6.25 m from one of the vertical walls. An Ono Sokki Precision Sound Level Meter type LA-5110 was used to take measurements of sound pressure levels in one-third octave bands at various receiver locations from 10 to 400 m. The receivers were located at the centerline of the tunnel and on the side at 2.65 m from one of the vertical walls. This is referred to as the offset line in this section. The height of the receiver was set at 1.3 and 2.38 m above the ground. These are referred to as the low and high positions, respectively.

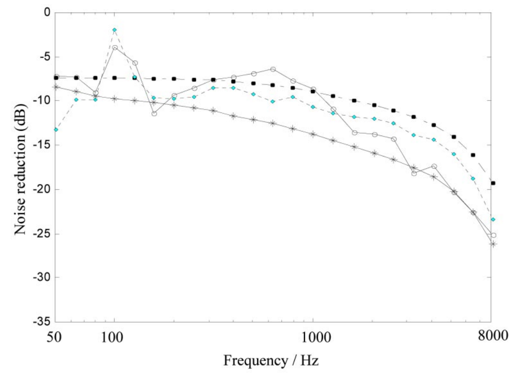

FIG. 7. A comparison of noise reduction spectra among the predictions by the coherent model, incoherent model, ASJ model, and measurements in Western Harbor Crossing Tunnel. The source and receiver were placed, respectively, at 0.9 and 2.38 m above the ground and at respective distances of 9.85 and 6.25 m from one side of the tunnel wall. They were separated by a horizontal distance of 250 m. The keys for the lines show in the figure are the same as in Fig. 3.

An initial measurement of the sound pressure levels at a horizontal distance of 10 m in front of the source was conducted in the tunnel. The result was used as the reference data for the deduction of the noise reduction spectra in our subsequent field measurements. At the reference location, the receiver was placed 1.3 m above the ground. A comprehensive set of measurements was then conducted for various source and receiver locations. These experimental data were used for a comparison with different numerical models. When the horizontal distance between the source and receiver was extended beyond 75 m, say, the noise levels dropped significantly due to the high absorption of sound energy in air, especially at frequency bands over 1 kHz. It is important to include the air absorption factor in the prediction models in order to accurately predict sound propagation in tunnels. To illustrate this point, selected noise reduction spectra are presented for the octave bands varying between 50 and 8000 Hz. Figures 7 and 8 display the results for receivers at a horizontal distance of 250 and 350 m from the source, respectively. In these two examples, the receiver was located at the centerline and at the high position. The figures reveal that the coherent model is able to predict peaks and

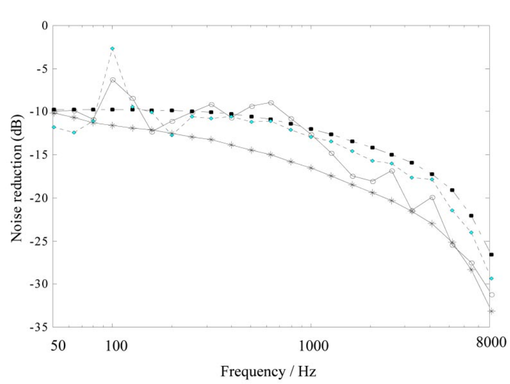

FIG. 8. The same as Fig. 7, except that the source and receiver were separated by a distance of 350 m.

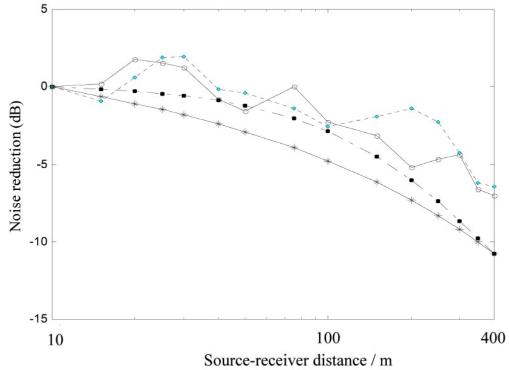

FIG. 9. A comparison of sound attenuation at different source/receiver separations along the Western Harbor Crossing Tunnel. The center-band frequency of the source was 50 Hz. The source and receiver were placed, respectively, at 0.9 and 1.3 m above the ground and both at a distance of 6.25 m from one side of the tunnel wall. The keys for the lines shown in the figure are the same as in Fig. 3.

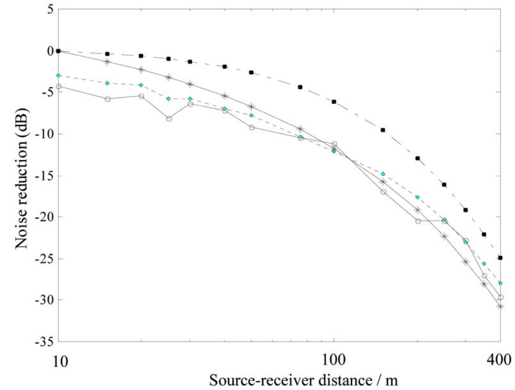

FIG. 10. The same as in Fig. 9, except that the receiver was located at a distance of 6.25 m from the same side of the tunnel wall and the center-band frequency of source was 6300 Hz.

dips occurring at the low-frequency region and gives the highest accuracy across the whole frequency range of interest as compared with the ASJ and incoherent models. In this geometrical configuration, the ASJ model underestimates the noise reduction of up to 6 dB at 3150 Hz, where destructive interference occurs. On the other hand, the incoherent model overestimates the noise reduction of up to 6 dB at 100 and 630 Hz, where constructive interference occurs.

As discussed in the last section, we can roughly estimate the critical frequencies, f_c, for these two examples in Figs. 7 and 8. According to Eq. (6), they are about 2 and 3 kHz for the horizontal distances of 250 and 350 m, respectively. We expect that the incoherent model should be adequate to estimate the average levels of the transmitted noise if the source frequency is higher than the critical frequency. This is supported by the experimental results shown in Figs. 7 and 8 in which the incoherent model gives a fair estimation of the Noise Reduction in the tunnel. Nevertheless, the incoherent model can only provide the average noise levels and are unable to predict the variation of NR in the spectrum as shown in the figures.

To prove the robustness of the coherent model in predicting sound attenuation along the tunnel in a long range propagation and at all frequencies of interest, noise measurements were conducted from horizontal distances of 10 to 400 m from the source, with the mid-band frequency ranging from 50 to 8000 Hz. To present the results, we have chosen only two representative sets of data for the purposes of illustration in the following paragraphs. Similar results comparing the experimental data with theoretical predictions can be found elsewhere.[12]

In the first set of experimental data, the noise source was set at the centerline and at 0.9 m above the concrete ground. The receiver was located at the centerline, and the center-band source frequency was 50 Hz. The noise reduction along the tunnel at various one-third octave bands are plotted to compare the measurement results with the predictions by various models. Figure 9 illustrates that the predictions by the coherent model give the best agreement with the measurement results for sound propagation up to 400 m. It also shows that a strong constructive interference effect occurs at receiver locations at a distance of between 20 and 30 m. Redmore[13] referred to this phenomenon as a "plateau" in his experimental data. In our case, both the incoherent model and the ASJ model overestimate the noise reduction, and the discrepancies become relatively large at distances when destructive interference occurs.

In the next set of data, the receiver was shifted to the offset line and at 2.38 m above the ground. The center-band frequency of the source is 6.3 kHz. Despite the fact that the interference effect becomes less significant at high frequencies, Fig. 10 shows that prediction results by the coherent model agree very well with the measurements at this set of data for the separation between the source and receiver extending to 400 m. The results predicted by the ASJ model appear to be the least accurate in this example. Similar conclusions can be drawn based on the comparison of measured and predicted results for other geometrical configurations but these results are not shown here for brevity.

IV. SUMMARY

The experimental data for the full-scale field experiments at Tai Lam Tunnel and Western Harbor Crossing Tunnel confirms a finding in a recent study on scale model experiments. The coherent model gives the best agreement with experimental results among all three prediction schemes, particularly at the low- and mid-frequency regions. The variation of the noise reduction at different frequencies is a feature that can only be predicted by the coherent model with accuracy to within 3 dB. The effect of mutual interference caused by the direct and reflected rays is an important factor for the accurate prediction of sound fields in long enclosures.

The incoherent model generally gives satisfactory predictions when the total sound field shows a less significant effect of interference between contributory rays. This will occur when the source frequency is sufficiently high and when the separation between source and receiver is small. For instance, as shown in a typical set of experimental measurements, the agreements are good for a source frequency of 6.3 kHz and a horizontal separation of 30 m. In this case, the total sound field can be approximated by summing all contributory rays incoherently.

Although the coherent model gives reasonably accurate results in most cases, some discrepancies between the field data and theoretical predictions are found. This is probably due to the scattering of sound from the raised walkway adjacent to the vertical walls and other scattering surfaces hung from the ceiling. The fact that the tunnel section is not a true rectangular shape also affects the results.

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