Prediction of interior noise in buildings, generated by underground rail traffic

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Abstract

The prediction of sound field in cavities surrounded by vibrating walls is a simple task nowadays, provided that the velocity distribution along the walls is known in sufficient detail. This information can be obtained from a structural FE calculation of the building, and the results can be led directly into a conventional Boundary Element analysis. Though methodically simple, it is not an attractive way of prediction from the practical point of view: the size of the matrices needed for BE calculation is too large, thus the inversion of them is very cumbersome and computation intensive.

The paper introduces a modified numerical calculation method, being apt for practical calculations without the need of constructing and inverting large matrices. The suggested method is based on the Rayleigh radiation integral and some standard direct (collocational) BE techniques, where the necessary input data are generated from measured or calculated velocity values in just a few points. The technique has been compared and validated on the basis of an extensive measurement series, performed in a concrete building close to a tunnel of line B of the underground railway network RER in Paris.

1. Introduction

It is a typical task of the acoustic engineer to predict interior noise levels generated by structural vibrations. The source of structural vibration may be either a railway line running beside a building or a not properly vibration isolated machinery inside the building, for the prediction of reradiated noise we need detailed information on the vibration distribution along the boundary surfaces. This can be determined by using finite element modelling. To predict the noise from the vibration velocities, the most accurate way is using boundary element method (BEM) [1,2,3]. The advantage of BEM is that it can be applied to arbitrary shaped enclosures and it can be easily connected to the structural FE modell of the building. The disadvantage of it is that BEM is a low-frequency method. In the case of a typical room, for calculations in the mid-frequency range the resolution of the boundary mesh should be increased and that would result a large system of linear equations to be solved. Inverting a fully populated matrix is very time consuming and despite the rapid development in size of the memory modules swapping is still required for real-life problems, slowing down the process considerably.

Another possibility to predict reradiated noise is using analytical formulas. For this we need the radiation efficiency of the walls. Radiation efficiency varies rapidly in the low-frequency range and is hard to determine. These formulas are simple and give rather rough results.

To solve exterior radiation problems Rayleigh integral based methods are well known and widely used. In this paper a new and simple way to predict interior noise levels is presented. The method calculates directly from the vibration and geometrical data of the room just like the analytical calculation, but there is no need of knowledge of radiation efficiency. As compared to BEM, the matrix describing the phenomenon is smaller and the inversion of it is also unnecessary.

2. Description of Rayleigh integral based method

If we know the surface normal component of the vibration velocity distribution along an infinite plane ($v_n(\boldsymbol{r})$), we can use the Rayleigh integral to calculate the radiated sound pressure in an arbitrary point ($\boldsymbol{q}$) of the space [4,5]:

$$p(\boldsymbol{q},\omega)=\iint_{\Sigma} g(\boldsymbol{r},\boldsymbol{q},\omega)v_n(\boldsymbol{r})d\Sigma \tag{1}$$

where

$$g(\boldsymbol{r},\boldsymbol{q},\omega)=\frac{e^{-jk(\boldsymbol{q}-\boldsymbol{r})}}{|\boldsymbol{q}-\boldsymbol{r}|} \tag{2}$$

is the Green's function of the homogeneous acoustical full-space, $k = \omega / c$ the wave number, ω is the circular frequency, and c is the speed of sound.

If we apply the Rayleigh integral to the case of closed spaces, we get a rough estimation of the radiated sound pressure. The result is the sum of sound pressures radiated by each wall to an acoustical half-space. Each wall is handled separately as part of an infinite plane. Only a small part (ie. the wall) of the infinite plane vibrates, the surface normal vibration velocity along this part is known, and $v_n = 0$ otherwise:

$$p(\boldsymbol{q},\omega)=\sum_{n=1}^{N}\iint_{\Sigma_n} g(\boldsymbol{r},\boldsymbol{q})v_n(\boldsymbol{r})d\Sigma \tag{3}$$

where N is the number of walls.

To take into account not only the primarily radiated sound but the reflections from the walls, we have to modify the Green's function (2). Each reflection can be handled as a direct sound source (image source), the location of which is determined by mirroring the originally radiating part of wall to the reflecting walls, and the amplitude of which is reduced proportionally to the absorption at the reflections:

$$\hat{g}(\boldsymbol{r}_0,\boldsymbol{q},\omega)=\frac{e^{-jk(\boldsymbol{q}-\boldsymbol{r}_0)}}{|\boldsymbol{q}-\boldsymbol{r}_0|}+\gamma_1(\omega)\frac{e^{-jk(\boldsymbol{q}-\boldsymbol{r}_1)}}{|\boldsymbol{q}-\boldsymbol{r}_1|}+\ldots+\gamma_i(\omega)\frac{e^{-jk(\boldsymbol{q}-\boldsymbol{r}_i)}}{|\boldsymbol{q}-\boldsymbol{r}_i|}+\ldots \tag{4}$$

where $\boldsymbol{r}_i$ is the location of the i-th image source and $\gamma_i(\omega)$ represents the effect of absorption.

This method is rather complicated in the general case, for a large number of image sources has to be taken into account, and also their location and visibility has to be determined individually.

For simplicity, our investigations are restricted to the case of shoebox shaped rooms. This restriction enables us to neglect visibility tests and the determination of the location of the image sources can be easily automatized.

In the following we assume that the absorption of the walls is constant, represented by $\Gamma(\omega)$. With this we can convert (4) to the following form:

$$\hat{g}(\boldsymbol{r}_0,\boldsymbol{q},\omega)=\frac{e^{-jk(\boldsymbol{q}-\boldsymbol{r}_0)}}{\left|\boldsymbol{q}-\boldsymbol{r}_0\right|}+\Gamma(\omega)\sum_{k=1}^{K_1}\frac{e^{-jk(\boldsymbol{q}-\boldsymbol{r}_k)}}{\left|\boldsymbol{q}-\boldsymbol{r}_k\right|}+\ldots+\Gamma(\omega)^m\sum_{k=1}^{K_m}\frac{e^{-jk(\boldsymbol{q}-\boldsymbol{r}_k)}}{\left|\boldsymbol{q}-\boldsymbol{r}_k\right|}+\ldots \tag{5}$$

where K_i is the number of the i-th order reflections.

The surface integrals in equation (3) are performed numerically. The whole surface is divided into surface elements of constant velocity distribution. The integration of the Green's function over the elements can be carried out by means of Gaussian Quadrature integration. The discretized form of (3) is:

$$p(\boldsymbol{q},\omega)=\sum_{i=1}^{N_e}v_{n_i}\sum_{s=1}^{N_p}w_s\hat{g}(\boldsymbol{r}_{i,s},\boldsymbol{q},\omega) \tag{6}$$

where N_e is the number of elements, N_p is the number of Gaussian points, v_{n_i} is the surface normal velocity of the i-th element, w_s is the Gaussian weight and $r_{i,s}$ is the location of the s-eth Gaussian point on the i-th element.

3. Numerical testing results

To verify and validate the newly designed prediction method, numerical tests were performed by means of shoebox shaped room of size 4 m x 5 m x 3 m . The method of the numerical testing was to calculate the internal noise in different points by means of direct BEM and the Rayleigh-based method, assuming a normal velocity distribution on the walls [6].

In the first tests a simple case was examined to investigate the convergence of the new method. One surface element was chosen as the only vibrating wall section of the testroom and the sound field generated by this single element was calculated for different absorption coefficients and for different number of reflections taken into account. Absorption was changed from 0 to 50 percent and number of reflections were increased from 0 up to 9261 (zero reflections mean applying the original Rayleigh integral to the walls). The results showed what had been expected: with increasing absorption the fluctuations in the response decrease, and with increasing the number of reflections the modal behaviour of the room can be observed more and more clearly.

In the second series of tests the effects of spectral and spatial averaging (dithering) were examined for several velocity distributions along the walls. Figure 1 shows narrow and third octave band spectra of noise levels calculated in seven points located closely around one internal point, assuming constant velocity distribution all over the room's surface. The maximum distance between two points is 0.2 m. The black solid line shows the third octave band spectrum averaged to the seven points. It can be clearly seen that although the narrow band spectra can show significantly different levels (mostly at the peaks and dips), the smooth curves obtained by spectral averaging are similar for the case of the two methods. The necessity of spatial averaging is also shown.

Figure 2 displays narrow and third octave band spectra in three points (averaged from 3x7 points) inside the enclosure assuming a more complex velocity distribution. The modal behaviour of the room is clearly shown by the narrow band spectra calculated by the two methods, and the spectral averaging allows to get similar results not only in the modal frequencies, but also in the noise levels.

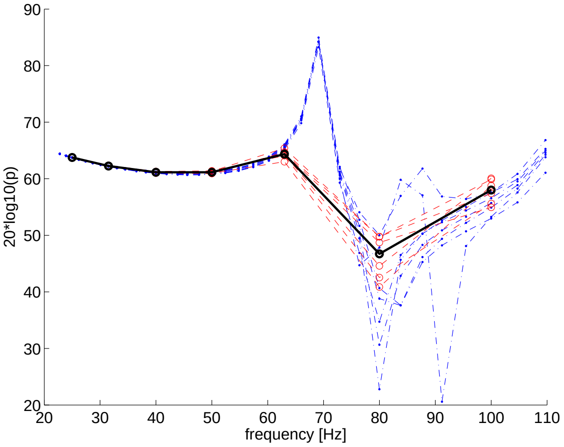

Fig. 1. The effect of spectral and spatial averaging. Dashed lines show narrow band spectra in 7 points located closely around the internal point, Solid line shows third-octave band spatially averaged spectrum. Left: boundary element calculations, Right: Rayleigh-based calculations.

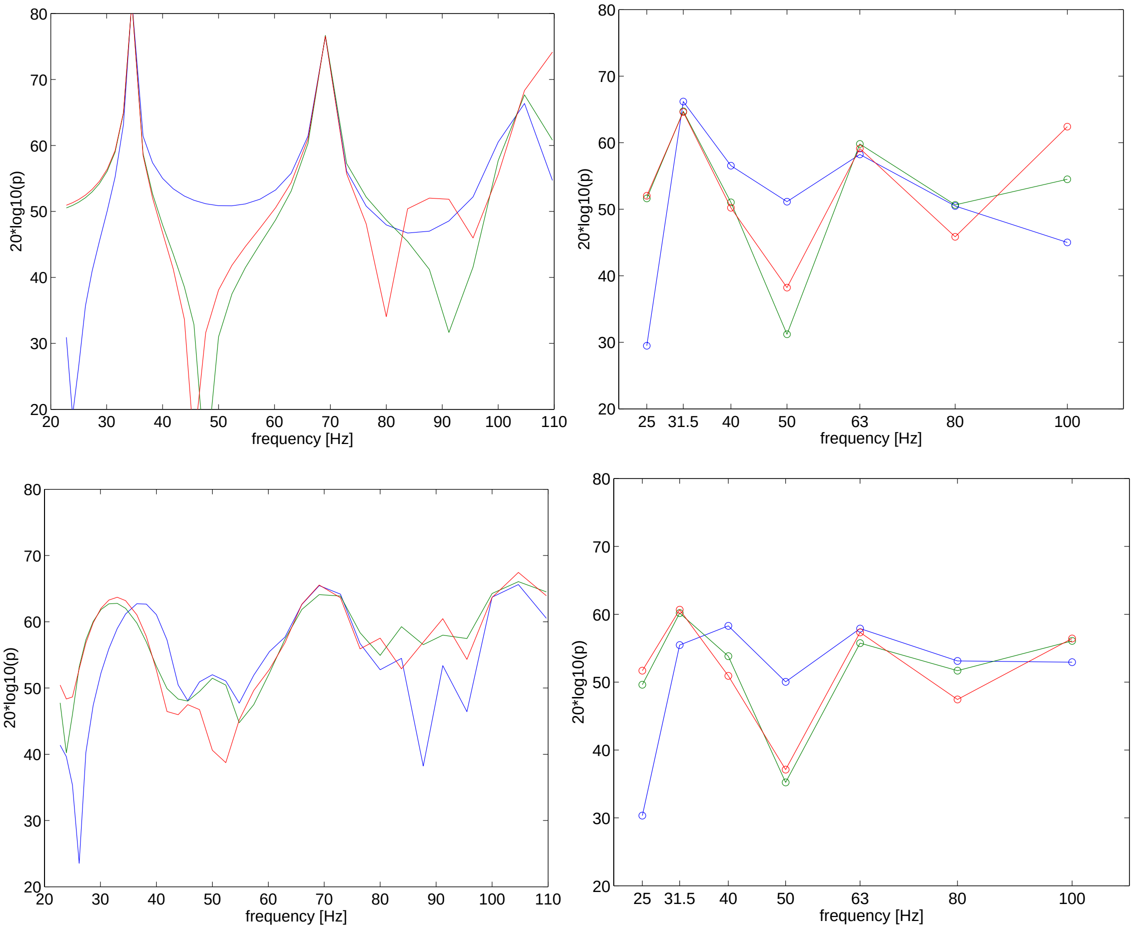

Fig. 2. Narrow and third octave band spectra in three points inside the enclosure. Left: narrow band, Right: third octave band spectra. Upper: results of boundary element calculation, Lower: results of Rayleigh-based calculation

4. Experimental validation

4.1. Noise and vibration measurements

For the experimental validation of the newly developed technique, extensive measurement series was performed in a concrete building close to the tunnel of line B of the underground railway line network RER in Paris.

Fig. 3. The measurement site in the basement with accelerometers on the ceiling.

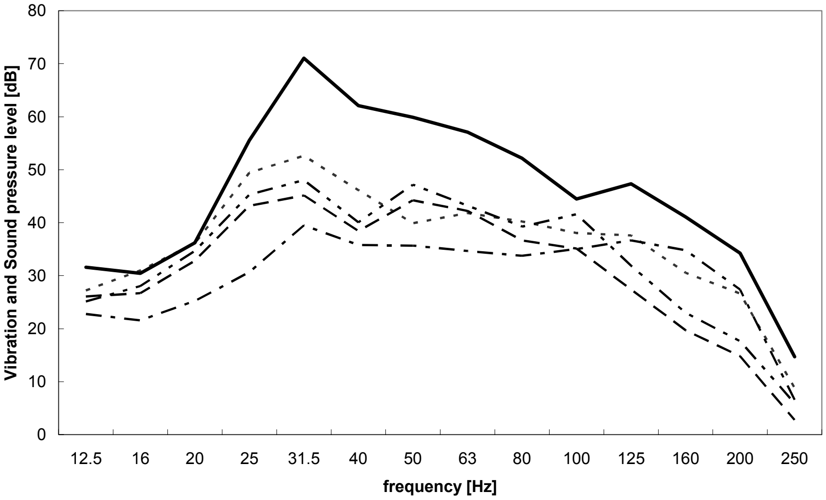

Fig. 4. Typical vibration and sound pressure levels during train passby. Dashed and dotted lines show vibration levels (re 5e-8 m/s) and the solid line shows sound pressure level (re 2e-5 Pa)

A room of 4.5 m x 5.8 m x 3.4 m was selected in the basement of the building with little furniture and clear concrete walls (see Fig. 3). By using a parallel measurement system of 16 vibration and 6 noise channels more than 80 train passbys were recorded, out of which 62 were good enough to be evaluated. Sound pressures were measured in 6 points, vibration was measured altogether in 56 plus 1 reference point, providing a good quality data set suitable for model validations. Typical vibration and noise levels during a typical train passby can be seen in Figure 4.

4.2. Numerical modelling

As input for the BE and Rayleigh-based calculations, a dense boundary mesh is required was needed with velocity values in each nodes of the mesh. Linear interpolation was used to get the vibration distribution along the walls from the 57 measurement points. The mesh for interpolation can be seen in Figure 5, and the resulting boundary mesh representing the vibration values are shown in Figure 6. For the determination of the vibration distribution of the ceiling the results of experimental modal analysis were also used.

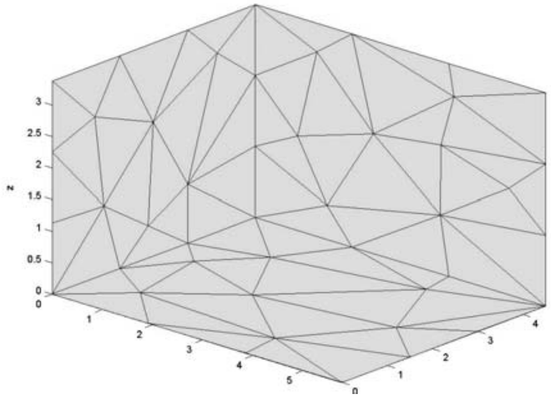

Fig. 5. The interpolation mesh used to generate vibration distribution input for the calculations

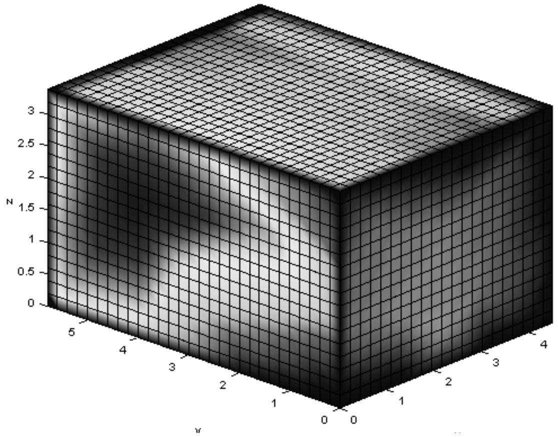

Fig. 6. The vibration distribution along the bundary element mesh used as input fot the calculations

4.3. Comparison of results

Fig. 7 shows the results of boundary element modelling in one of the 6 microphone positions compared to the measured values, whilst Figure 8 shows the results of the Rayleigh-based calculation (with different number of reflection orders).

It can be seen that both methods give good approximation in tendency, but differences between the results can reach up to 8-10 decibels at certain frequencies. If we express the results in equivalent A-weighted levels the Rayleigh-based method's best result is a difference of 1.3 dB, the worst is 3.4 dB, whilst that of the BEM is 0.4 dB and 1.2 dB respectively.

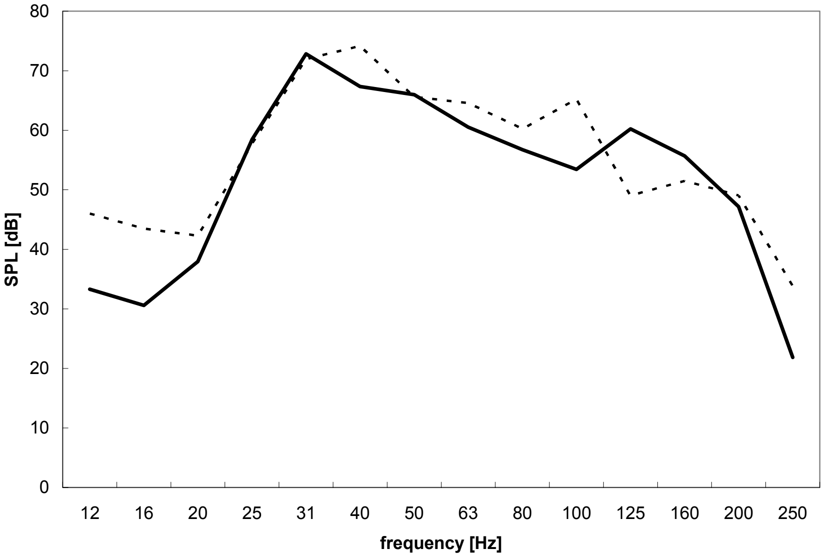

Fig. 7. Results of the standard collocational boundary element analysis compared to the measurement results. Dashed thin line shows calculated results, Solid thick line shows measured results.

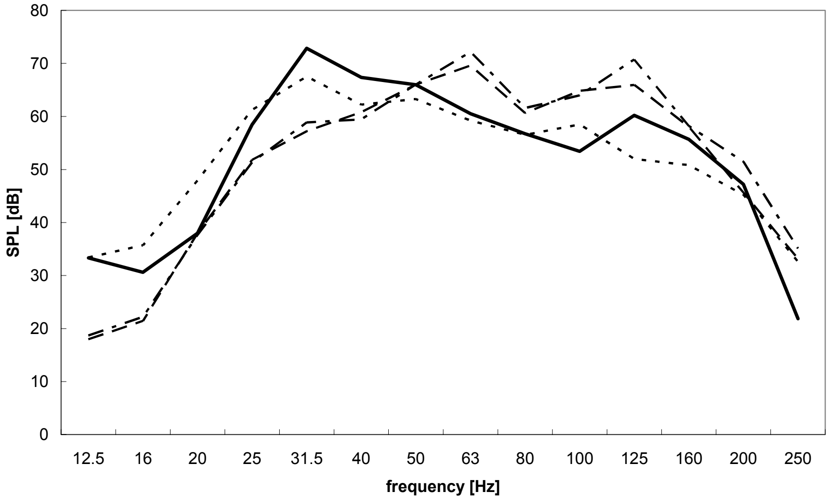

Fig. 8. Results of the Rayleigh-based calculation compared to the measurement results. Solid thick line shows measured results, dashed and dotted lines show results of Rayleigh based calculation with different number of reflections taken into account.

5. Conclusion

In this paper we have presented a newly designed, simple method for predicting radiated noise levels in enclosures. The method is based on the Rayleigh integral and uses a modified Green's function, which gives the sound field in an arbitrary point in a shoebox shaped room, due to a point source placed on the boundary surface. It is also assumed that acoustic absorption is evenly distributed along the walls of the room and can be described by a constant, frequency dependent absorption coefficient function.

The method was verified by comparison with the conventional collocational boundary element method, on the basis of both numerical experiments and an extensive measurement series of parallel noise and vibration measurements under real-life conditions. Investigations have shown that the results of the two different methods are in good agreement, provided that both spatial and spectral averaging is used.

According to the results it can be stated that the Rayleigh-based method gives reliable results without the disadvantage of creating and inverting large matrices.

Acknowledgements

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References

[1] J.P. Coyette and J. Van de Peer, Acoustic Boundary Elements, in *Advanced Techniques in Applied and Numerical Acoustics,* Leuven, 1997, paper n. 7.

[2] O. von Estorff, *Boundary Elements in Acoustics: Advances and Application,* WIT Press, Hamburg-Harburg, 2000

[3] R. J. Bernhard, B. K. Gardner, C. F. Mollo and C. R. Kipp, *Prediction of Sound Fields in Cavities Using Boundary-Element Methods,* Journal of American Institute of Aeronautics and Astronautics, 25(9):1176-1183, 1986

[4] A. D. Pierce, *Acoustics,* Acoustical Society of America, New York, 1991.

[5] F. Fahy, Sound and Structural Vibration, Academic Press, London, 1985.

[6] A. B. Nagy, P. Fiala, F. Augusztinovicz, A. Kotschy, Prediction of radiated noise in enclosures using a Rayleigh integral based technique. Paper accepted for publication at Interoise 2004, Prague, 22 to 25 August.