PREDICTION OF THE SPEECH TRANSMISSION QUALITY IN THE PRESENCE OF BACKGROUND NOISE USING THE RAY TRACING TECHNIQUE

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Noise levels inside commercial aircraft and automobile impact both the quality of the speech communication between the crew members and the communication between the crew and passengers. Noise measurements are expensive and have significant variability. Therefore, geometrical techniques can be used as an alternative to predict the steady state frequency response or the impulse response. This paper presents a ray-based technique to predict the acoustic response and speech transmissibility indices inside aircraft and automobile. The effect of the background acoustics levels on speech communication is analyzed. Moreover, the effect of the acoustic treatments on the reflected field and its interference with the direct field perceived by the listener is analyzed.

Keywords: Ray Tracing, acoustic wave, background noise, Speech Intelligibility

1. Introduction

Speech intelligibility constitutes an essential characteristic of the quality in vehicles such as aircraft, cars, trains, etc. The sources of noise causing high-level interior background noise which may affect the quality of the speech vary from one type of vehicle to another. The sources most responsible for noise are the aerodynamic flow, fans, internal turbomachinery, propeller, rotors, exhausts, engine combustion etc., [1]. These sources represent either airborne or structure borne excitations that are transmitted through the outer section of a vehicle and generate interior background noise. This noise provokes serious discomfort and fatigue of crew and passengers, and potentially endangers the safety of flight or driving [2]. Measurement of the transmitted noise level is often expensive or difficult to perform during early stages of design before test hardware is available; therefore, numerical simulations are used as an alternative. Often, discretization methods such as finite element and boundary element (FE/BEM) are used
due to their accuracy in predicting interior noise generated by airborne or structure-borne excitation. However, these techniques are computationally expensive. Geometrical techniques are often used to analyse the acoustic wave propagation inside a building. However, they are rarely used to analyse the acoustic wave propagation in vehicles because of the lack of modelling structural wave propagation. Application of ray tracing method is generally conducted for modeling of sound propagation in an enclosed space or room [3-6]. The image-source technique considers that the total energy received at an observation point is the sum of direct energies radiated by the sources and their images through the reflecting faces. The image technique has been successfully employed to analyse the sound propagation inside buildings [7-8]. The combined ray-tracing/image-source technique consists of using ray tracing to detect the virtual image sources contributing to the response at the receiver [9]. In order to make a reliable evaluation of interior or exterior noise, geometrical acoustics must account for wall absorption and include diffusion and diffraction effects. The diffusion defines how much energy should be reflected specularly and how much should be reflected in random directions. The diffraction of the wave by finite-dimension walls is still an open question. In acoustics, the diffraction may be important in the shadow zone where only diffracted acoustic field exist. However, its contribution is generally low compared to the direct and reflected acoustic field in the illuminated frontal side of the reflecting face. Even if the diffraction importance is not dominant for certain receiver locations, research is still in progress to account for its effect [10-12]. Recently, an efficient approach has been presented in reference [13] that combines the FE/BEM approach to ray-tracing to evaluate the acoustic wave transmission through a structure excited by airborne and structure-borne excitation. Indeed, the loaded structure is replaced by a compact acoustic source (CAS). A CAS is a source concentrated at a single point but with a defined directivity pattern. This is generally an efficient and effective way to represent a complex source as long as the acoustic wavelength is smaller than the distance between the source and the observation point. The directivity of CAS is characterized using coupled FEM/BEM approach. Then the acoustic field at the receivers is evaluated using the ray tracing technique which consider the source directivity pattern predicted using the FEM/BEM-approach. The presented work was limited to steady state analysis.

In this paper, the same technique presented in reference [13] is adopted to predict the background noise due to airborne and structure-borne sources and the predicted background noise is introduced as an input to predict the speech transmission quality inside car and aircraft using the ray tracing technique. Moreover, a combined SEA-ray tracing strategy to predict speech clarity indices is herein presented. The effect of the material properties and surface condition is also accounted for. The accuracy of the ray tracing technique in predicting the noise level generated by different sources as well as the speech intelligibility indices are evaluated by comparison with full (BEM/FEM) predictions and good agreement is found.

2. Theory

The focus in the first section of theory will be on the mathematical model to evaluate the total acoustic field generated by the compact acoustic sources (CAS) with directivity which radiate in the vicinity of reflecting faces. Next, the mathematical formulations to compute the speech clarity indices are presented.

2.1 Prediction of the frequency response:

In the ray tracing technique, the source of noise is a compact acoustic source. The acoustic response at a given location generated by a CAS can be computed using the image source technique. The latter allows representing a boundary element problem in terms of an equivalent problem involving virtual image source without boundary. Indeed, for an omnidirectional source with strength $Q_s$ radiating above the reflecting face, the acoustic pressure at any location point “$N$” above the reflecting face can be obtained as [14]:

$$p(N) = \sum_{i=1}^{N} q_i \cos(\theta_i)$$
\[ p(N) = -A_i(f)e^{j\varphi_i}\{G(r) + \Re(\theta)G(r')\}. \] (1)

Where \( G \) is the free field Green function. \( \Re(\theta) \) is the reflection coefficient. The first term in equation (1) correspond to the direct field from the source and the second term correspond to the direct field from the source - image.

In the presence of multiple sources and faces and by assuming that the acoustic field is smaller than the size of the reflecting faces, the total filed at a given point is the sum of all the direct field of all the sources and their images.

\[ P_{total}(N) = \sum_i D_i A_i e^{j\varphi_i} \sum_m \Re_{ml} G(r_{ml}). \] (2)

where \( D_i, A_i \) and \( \varphi_i \) are the source directivity, the source amplitude and the phase of the \( i \)-th source. \( \Re_{ml} \) is the reflection coefficient.

### 2.2 Speech intelligibility

The Speech Intelligibility is defined as a measure of the proportion of the content of a speech message that can be correctly understood. To measure the clarity of the speech, the speech transmission indices (STI) and the room acoustic speech transmission indices (RASTI) are adopted in this paper. The following describes the STI and RASTI methods based on the 2011 version of the international standard

#### 2.3 STI method

In the STI method, the transmission in 7 octave bands from 125 Hz to 8 kHz is considered separately. For each octave band, the modulation transfer function is evaluated at 14 discrete modulation frequencies in one-third octave bands from 0.63 Hz to 12.5 Hz which gives a total of 98 results \( m_{k,f_m} \). Initially, the effective signal to noise ratio (in dB) is calculated for each result as [16]:

\[ SNR_{eff,k,f_m} = \log_{10} \frac{m_{k,f_m}}{1 - m_{k,f_m}}, \] (3)

where, \( m_{k,f_m} \) is the modulation transfer function at a specific modulation frequency \( f_m \) at band \( k \).

The values of \( SNR_{eff,k,f_m} \) is limited to the range between -15 and 15 dB. In the next step, the transmission index is calculated for each result as:

\[ TI_{k,f_m} = \frac{SNR_{eff,k,f_m} + 15}{30}, \] (4)

which ranges from 0 to 1. This allows computation of the modulation transfer index (MTI) which is the average \( TI \) for each band. The STI is then computed as:

\[ STI = \min \left(1.0, \sum_{k=q}^7 \alpha_k MTI_k - \sum_{k=q}^6 \beta_k \sqrt{MTI_k MTI_{k+1}} \right). \] (5)

where \( \alpha_k \) is the weighting factor for band \( k \) and \( \beta_k \) is the redundancy factor between bands \( k \) and \( k + 1 \). \( q \) is 1 (corresponding to the 125 Hz band) for male and 2 (corresponding to the 250 Hz band) for female speakers.
2.4 RASTI method

The RASTI method is a reduced version of the STI method, where only the 500 Hz and 2000 Hz octave bands are taken into account. Instead of 14 modulation frequencies, only 4 modulation frequencies are used for the 500 Hz band and 5 modulation frequencies are used for the 2000 Hz band which gives a total of 9 results [16]:

\[
RASTI = \frac{SNR_{RASTI} + 15}{30},
\]

where the \(SNR_{RASTI}\) average is given by:

\[
SNR_{RASTI} = \frac{1}{4} \sum_{m=1}^{4} SNR_{eff\,500,f_m} + \frac{1}{5} \sum_{m=1}^{5} SNR_{eff\,2000,f_m}.
\]

where the \(SNR_{eff}\) values are calculated as for the STI, i.e. there will be 9 values which are limited between -15 and 15 dB.

3. Numerical results and discussion.

In the following section, numerical validations and discussions are presented. The method used to prediction the background noise and speech clarity indices will be referred to as ray tracing.

3.1 Speech intelligibility in room acoustics

The aim of this example is to analyze the effect of the background noise generated by a loaded flat plate on the speech transmission quality in a closed acoustic volume. A point force excitation on a plate coupled to an acoustic cavity is considered. The acoustic pressure inside the cavity is predicted using combined ray tracing-FE/BEM approach in a first step. In a second step the predicted pressure is introduced as a background noise to predict the speech transmission indices (STI) and (RASTI) for an internal speaker located inside the acoustic volume. The plate is 1mm thick and made up of aluminum and the acoustic space dimension is 1.5x1x1 m\(^3\) (Figure 1). Each rigid wall of the cavity is treated so that the total absorption of the cavity is 70%. The elastic flat plate is embedded in the middle of the top face. The plate dimension is 0.5x0.3 m\(^2\) (Figure 1). To model this with ray tracing, the plate is replaced with a compact acoustic source with directivity. The directivity of the baffled plate is computed using BEM following the same process in reference [13]. Due to the high absorptian of the cavity, the fluid-structure coupling effect can be neglected as the reflected field is lowered and doesn’t affect the dynamic behavior of the plate. The accuracy of background noise prediction using ray-tracing is examined by comparison with full FEM/BEM prediction. Figure 2 shows a good agreement between the ray tracing prediction and the FEM/BEM prediction. The small discrepancies between Ray Tracing and BEM are related to phase of the acoustic wave. Indeed, due to the spreading of the acoustic ray, the latter doesn’t hit exactly the center of the receiver. Hence, the total distance traveled by the ray from the source to the receiver is slightly higher than the distance between the source and receiver center where the BEM prediction is evaluated.
Next, the predicted pressure is averaged over several points in the space and introduced as a background noise inside the cavity. The speech clarity indices for a speaker located at position (0.5m, 0.8m, 0.2m) are then predicted at different receiver locations. The histograms in Figure 2 show the predicted STI and RASTI at each receiver where the magnitude of the point force is varied from 1N to 10N. It is observed that both the STI and RASTI decrease by increasing the background noise. Also, for a given background noise level, the speech clarity indices decrease by increasing the distance between the source and the receiver.

![Figure 3: Speech intelligibility indices: a) STI - b) RASTI](image)

### 3.2 Car Interior

In the following example, the speech intelligibility is evaluated inside a car at the driver and the passenger ear positions for a loudspeaker located on the dashboard of the car as shown in Figure 4-d. The background noise is generated by a diffuse acoustic field applied on the side glass (Figure 4-a). The background noise is predicted using the ray tracing in a first step. The loaded side glass is replaced by a compact acoustic source with directivity (Figure 4-b). To predict the speech clarity indices using ray tracing the car geometry is subdivided into reflecting faces (Figure 4-c).
The effect of the background noise on the speech transmission quality is evaluated for different background noise levels. The accuracy in predicting the background noise using ray tracing is examined by comparison with FEM/BEM prediction and hybrid SEA/FEM prediction using VA One commercial software [18]. Figure 5-a shows good agreement between the ray tracing approach and VA One predictions. It is also observed that the ray tracing provides good result in a shorter time compared to BEM.

The histogram in Figure 5-b shows the STI predicted using ray tracing with the internal loudspeaker modeled as a compact acoustic source. It is observed that by increasing the background noise five times above the initial level, the STI goes to zero at the location of the passenger ear position in the rear seat locations.

3.3 Airplane interior

The last example is concerned with the speech transmission quality inside of an airplane subjected to diffuse acoustic field (DAF), turbulent boundary layer (TBL) and point force loads which generate an interior background noise field. The pressure level inside the airplane corresponding to each of the previous sources is evaluated first using the Statistical Energy Analysis (SEA) module in VA One commercial software [18]. This pressure is then introduced as a background noise for a speech clarity analysis using the ray tracing approach. A speaker located in the front of the airplane cabin is modelled as a Compact Acoustic Source (CAS) as shown in Figure 6.
Figure 6: aerodynamic load and mechanical loads applied on the fuselage of an airplane.

The STI at different listener locations inside the airplane for different background noise corresponding to each load is presented in Figure 7-a. The space between receivers is 1m. In this example it is observed that the TBL excitation has the most important impact on the speech intelligibility. Also, the STI decreases as the distance between the source and the receiver increases. Figure 7-b shows the predicted RASTI on the midplane of the airplane where the background noise is generated by a DAF, TBL and point force all together. It is observed that the RASTI decreases dramatically at rear seats of the airplane.

![Figure 7: Speech Transmission Indices a) STI - b) RASTI](image)

4. Conclusions

A geometrical acoustic approach based on ray tracing has been presented for calculation of the background noise generated by airborne and structure borne loads. The background noise is introduced as an input for speech clarity analysis. Both the STI and RASTI are evaluated using ray tracing including the effect of the background noise level. Detailed interaction of the acoustic ray with the geometrical and material properties such as the acoustic absorption are accounted for. Evaluation of the combined ray-tracing / image-source approach in terms of accuracy and solution time was performed versus numerical simulation. It was shown that the presented technique constitutes a reliable tool to perform a full steady-state and speech clarity analysis. Moreover, the presented technique is suitable for speech clarity analysis of large vehicles such as aircraft and automobile subjected to aerodynamic and mechanical loads.

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