Synthesis of pass-by railway noise

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Abstract
Pass-by railway noise is one of the main problems in the community. Typically pass-by railway noise is estimated using Leq or Lden in dB (A) and often these methods do not reflect the listener perceptual overview. It is therefore necessary to reduce the pass-by railway noise by synthesizing the noise characters into various segments. The segments could be based on the physical properties of rail vehicles like rolling, traction, pantograph, cooling system noise, etc. There are few other segments which are also based on the perceptual view of the pass-by railway noise like squeaking, rattling or beating (tadak, tadak). Several pass-by noises from Swedish rail vehicles were recorded using binaural technology according to ISO 3095. Recorded noise signals were then synthesized with the help of spectrogram analysis using Matlab. Validated synthesized sounds were used to create the virtual railway sounds for more pleasant listening. The results of the studies indicate that the rolling noise and broadband noise are mostly annoying for the long distance passenger rail vehicles.

1 Introduction

In Europe, around 40% of the population is estimated to be exposed to transport noise levels that are potentially dangerous to health. The effects of high levels of noise can vary from mild nuisance to sleep disturbance, and potentially serious long-term health effects. Railway noise affects fewer people. However, more high speed rail links are being developed, consequently, the problems associated with rail noise are increasing. In Sweden, the total trains usually run up to 500 per day in the big cities where 30% of the trains are freight trains. Swedish Environmental Protection Agency has made a policy for the newly constructed houses. The policies are: 30 dB(A) equivalent level inside the house, 45 dB(A) maximum level inside the house in the night time and 55 dB(A) equivalent level outside the house.

Railway noise consists of noise emanating from the engine (mostly diesel), the friction of wheels over the rails, turbulence of airflow over the structure (dominated at high speeds) and from whistle blowing. To achieve noticeable noise reduction in railways, sound levels of several of these sources have to be reduced simultaneously. To reduce the annoyance, caused by railway noise, noise control engineering solutions can no longer focus only on lowering the total produced sound levels, but the sound quality of the perceived sound should also be improved. Sound quality is nothing but the perceptual reaction that reflects the subjective acceptability of emitted sound. The quality of the total railway noise can be improved by modification of single noise source; this is in contrast with the sound levels of the total sound which can only be lowered now-a-days by the concurrent abatement of several noise sources.

2 Measurement of Pass by Railway Noise

The measurement of pass by railway noise signal is done according to ISO 3095 [1].The sampling frequency used for all the recordings was fixed as 48 kHz. All the measurements were recorded on DAT recorder for post processing of the measurements data. The speed of the train was measured by a Hand-Held Radar Speed Detector. The types of trains used for noise measurement and their measured speed data are as follows:

X2000 (X2) -178 km/h, X40 – 166 km/h, Inter city (IC) -172 km/h, Freight train (FT)- 101 km/h, Commuter train (CT)- 70 km/h.

The other conditions of the measurement were wind speed of 1 m/s, temperature + 7°C, humidity 84% – 86% and UIC 60 rail with 10 mm rail-pad.

3 Spectral Analysis of Railway Noise

The spectral contents of different train noises recorded at a distance of 7.5 m were analyzed with spectrogram. The pass by sound of the railway vehicle is an example of the non-stationary signal. For analysis of such a signal, instead of simple FFT analysis, Short-Time Fourier Transform (STFT) can be used [2]. In this work, the Discrete Short-Time Fourier Transform (DSTFT) is used for the time-frequency analysis of Railway sound signals. The DSTFT transforms the time-varying railway sound signal into time-frequency domain components. Eq. (1) gives the formulation of the DSTFT of discrete signal x (n), when frames with a constant length are considered.

$$DSTFT \quad \{x(n)\} = X[m,k] = \sum_{i=0}^{N-1} x[i+ms] \cdot w(i) \cdot \exp\left(\frac{-j2\pi ki}{N}\right) \qquad (1)$$

where, m is the frame index, k is the frequency index, N is the number of frequency points of DFT, S is the number of samples advanced between frames and *w*(i) is a window function. N and S control the frequency and time resolution of the spectrogram respectively. If N = S, then there is no overlapping of the signal between the time frames. In this case the frequency resolution can be improved at the cost of time resolution and vice versa. If N > S then overlapping occurs between the time frames by number of samples equal to N-S. In this way time resolution can be increased without affecting frequency resolution.

Time frequency spectra of five different railway sounds are analyzed with the help of Eq. 1. Frequency resolution for the spectra is selected as 6 Hz. Sound of passenger trains have shorter time duration (6 – 11 sec) compared to freight train (35 sec). Therefore, the numbers of time fragments (600-900) were also varied to achieve better time resolution. This means that some samples of each time fragment gets overlapped. It was assumed that the energy of the signal is constant while performing DFT on isolated short time fragment. The assumption made here was not correct as the signal being non stationary, but as the time fragments are very small the introduced error is expected to be quite small.
Figure 1 shows a time-frequency spectrum of X2000 train noise, measured at a distance of 7.5 m away from 1st rail line and at a height of 1.2 m above the surface of the railway line.

This spectrogram shows the time distribution of energy in the sound across frequency.

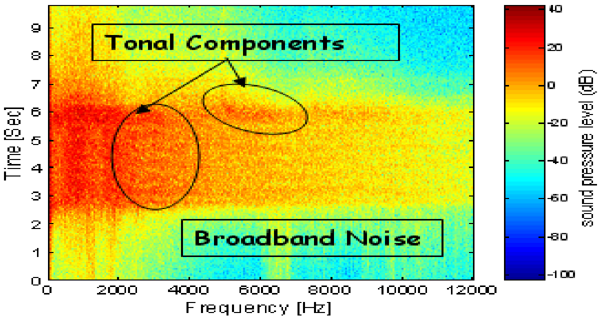

Figure 1 Time frequency spectrum of X2000 train noise

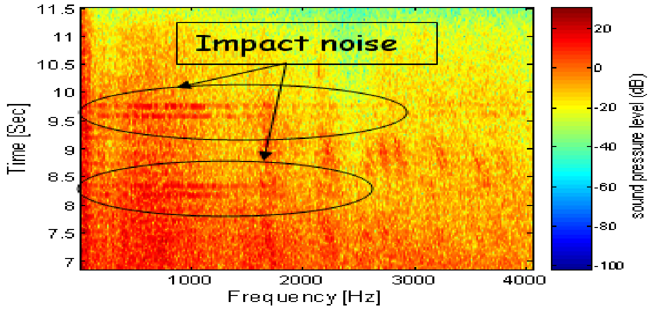

Figure 2 Time frequency spectrum of Commuter train

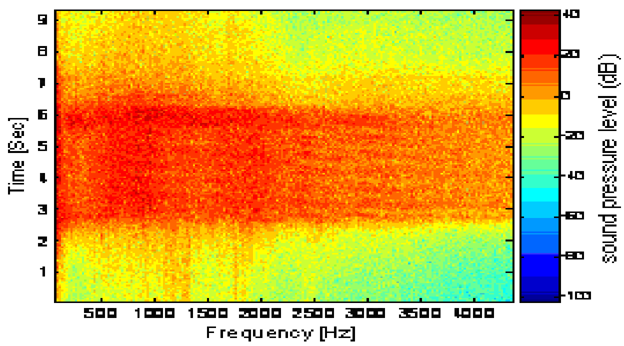

Figure 3 Time frequency spectrum of X2000 train noise that depicts tones due to rolling wheels

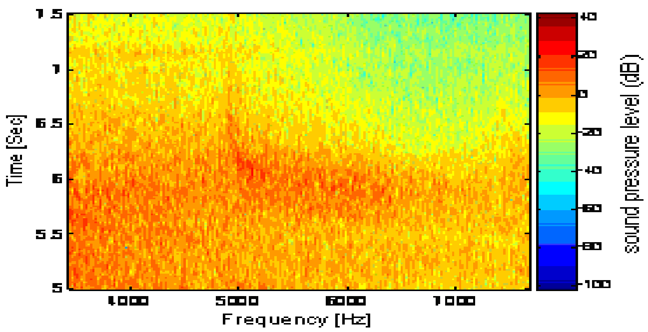

Figure 4 Time frequency spectrum of X2000 train noise depicting other tone due to auxiliary equipment

For synthesis, railway noise is divided into three different components:

(i) Doppler shifted tonal components, (ii) broadband noise, and (iii) impact (tadak-tadak) noise. 1st two components can be seen in figure 1 and the last component can be found in figure 2. Some of the tonal components are observed in a bunch of few numbers of tones and some tonal components are observed as a single tone only. Figure 3 shows the tones that are observed in bunches while figure 4 shows a tone that is observed as a single tone. Two bunches of seven tones of X2000 train noise can be clearly seen in figure 3. The frequency range of Doppler shifted tones in first bunch can be seen from approximately 2.25 – 2.75 kHz and the frequency range for the second bunch can be seen from approximately 2.75 – 3.25 kHz. These seven different tones are spaced at approximately equal time intervals from 2 sec to 6 sec. The number of tones in a bunch depends on the number of railway compartments.

From figure 5 it is clear that the distance between bogies A and B is 7.25 m while the distance between bogies B and C is 17.7 m with the speed of X2000 train being 178 km/hr. (49.44m/sec). Therefore, it can be concluded that the four tones generated by four the wheels of bogie A and B are perceived as one tone as these wheels pass the microphone within very less period of time. Four wheels of another bogie C and D make another tone and so on. Therefore, X2000 train should produce seven tones as it has total six compartments including power car.

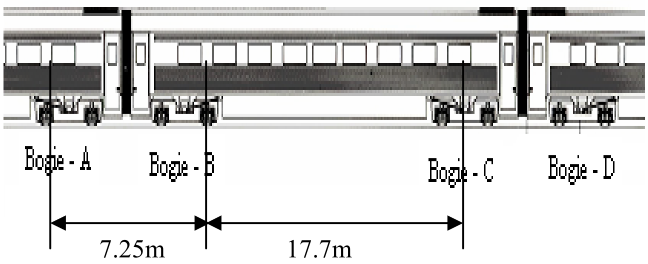

Figure 5 Generation of tonal components from rolling wheel. (Distances are taken from configuration of X2000 train).

Some tonal components are not observed in bunch instead they appear as a single tone only (Fig. 4). Frequency of this Doppler shifted tone lies between 5 - 6.5 kHz and the time duration of this tone is from 5.5 – 6.5 sec. This type of tone is observed for longer period of time compared to the first type of tone. The origin of such tone is the components of HVAC devices or traction motors with frequency range between 125-800 Hz [3].

Broadband noise is generated by the aero-acoustics sources such as the turbulence around the vehicle structure (flow-obstacles interaction) and it is also originated by the forced air flow generated by cooling fans used in traction motors and HVAC devices. Third component is impact noise which is generated due to poorly aligned rail joints. Figure 2 shows the spectral contents for impact noise generated by commuter train.

4 Method for Synthesis of Railway Noise

To achieve the synthesis of all recorded railway noise, it is necessary to reconstruct three components i. e. all the tonal components, impact noise and broadband noise. Impact noise was not present in all sounds hence it was reconstructed only if it was present in the original sound. A MATLAB program was prepared for the synthesis of railway noise.

4.1 Synthesis of Tonal Components

Synthesis of all tonal components is based on simple principle of sinusoidal components with both amplitude and frequency varying with respect to time[4,5].

4.1.1 Time-frequency behavior

As can be seen in figures 3 and 4, the frequency of all tonal components is not same but it varies with respect to time and has a curved shape. Curve shape of tonal components is introduced because of the Doppler Effect.

During the implementation process, the user inputs one reference point by simply clicking on a tonal component in the time-frequency spectrum. The frequency corresponding to this point is the broadcasted frequency (f_b) and the time is the reference time (t_{ref}). With the help of this data, the Doppler shifted frequency of the tone is calculated at each instant of time by using Doppler formula and by calculating the relative speed of railway with respect to the microphone.

The calculated time-frequency data were further corrected in two stages. In the first stage user was given a chance to enter the corrected reference point till he gets satisfied with the time-frequency behavior. In the second stage, the correction of frequency is based on the amplitude of the tone at each time step in the spectrogram.

4.1.2 Amplitude of tonal component

The amplitude of every tonal component at each time step was estimated by using few numbers of samples in the vicinity of that time step. These numbers of samples depend upon the frequency estimated in previous section at each time step. The numbers of samples were calculated using Eq. 2 [4]. The number of samples chosen for calculation of amplitude of the tonal components corresponds to 20 times the time period of corresponding frequency at that particular time step. The hanning windowed DFT was calculated for this fragment of sound using Eq. 3. To speed up the process, the DFT was evaluated only for the frequency of the tonal component at that time.

$$N(m) = \left(\frac{1}{f(m)} \cdot 20 \cdot F_s \right) \qquad (2)$$

$$X[m,k] = \sum_{i=0}^{N(m)-1} x[i + \sum_{p=1}^{m-1} N(p)] \cdot w(i) \cdot \exp\left(\frac{-j2\pi ki}{N(m)} \right) \qquad (3)$$

The final synthesis of the tonal component is done as a sinusoidal component with time varying amplitude and frequency. Time frequency spectrogram of synthesized tonal components is shown in figure 6.

4.2 Synthesis of Impact Noise

The impact noise was simply separated from the original sound within the time at which impact occurs. This separated impact noise was further filtered within the certain frequency band. This is done because impact noise is dominated within certain frequency range only. Remaining frequencies cover broadband noise. Time frequency spectrogram of synthesized impact noise is shown in figure 7.

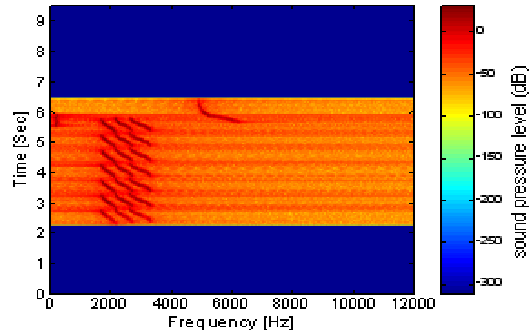

Figure 6 Time frequency spectrogram of synthesized tonal components of X2000 train

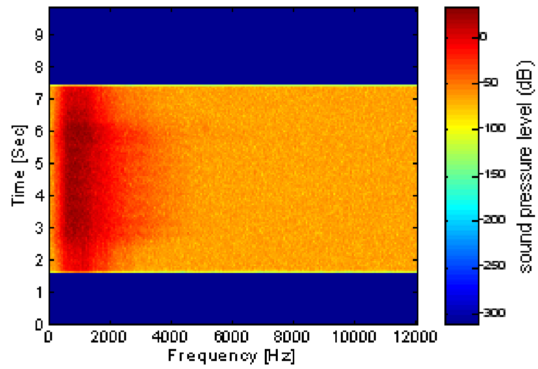

Figure 7 Time frequency spectrogram of synthesized Impact Noise of X2000 train

4.3 Synthesis of Broadband Noise

Synthesis of broadband noise is achieved in third octave band because of the analogy with the human hearing system. Broadband noise was synthesized up to 12.2 kHz as above this frequency not much energy is possessed by the sound signal. The amplitude of the broadband noise in each third octave band as a function of time is determined using Eq. 4.

$$E_i(t) = \sum_{k=N(i,t)} E(k,t) \qquad (4)$$

where, $E_i(t)$ = the energy of the signal in the i^{th} third octave band at time t, k is the frequency index, N(i,t) is the number of spectral lines of the signal in the i^{th} third octave band at time t that do not cover the number of spectral lines of tonal components and impact noise. This is chosen, because it was not possible to determine how much energy is possessed by the tones and by broadband noise.

Finally broadband noise was synthesized by filtering white noise in appropriate third octave band and shaping the amplitudes in time domain. The amplitude of the broadband noise at each time step was calculated by making the energy of the white noise equal with the energy of the signal calculated using Eq. 4. Time frequency spectrogram of synthesized broadband noise is shown in Fig. 8. Final synthesis of railway noise is done by adding all the three separately synthesized components (Fig. 9).

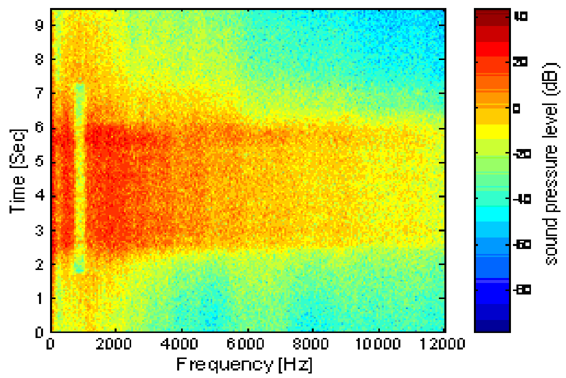

Figure 8 Time frequency spectrogram of synthesized Broadband Noise of X2000 train

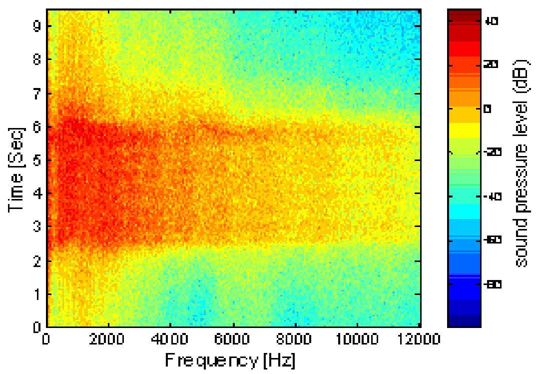

Figure 9 Time frequency spectrogram of final synthesized sound of X2000 train

5 Listening Tests and Analyses

Two listening tests were carried with the synthesized sounds. The aim of the first listening test was to validate the synthesized railway sounds and the aim of the second listening test was to test the virtual railway sounds for pleasantness.

5.1 Validation of Synthesized Railway Sounds (First Listening Test)

Jury of listener was asked to listen to the sounds carefully and was asked to answer two questions. In the first question, jury was asked to compare the sounds in each pair on the following scale: totally different (TD), different (D), moderately different (MD), slightly different (SD) or similar (S). In the second question, jury was asked that if they felt that the sounds in a pair were not similar then which sound out of two sounds was most realistic one.

Figure 10 shows the average judgments offered by the jury to each sound pair. It can be seen that for first four train sounds of X40, X2k, IC and CT the judgment given by jury varies between S and SD. Last three train sounds are of three fragments of the freight train. The judgment offered by the jury to these sounds is between SD and D.

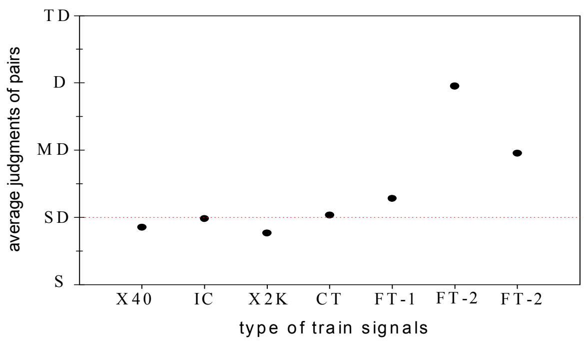

Figure 10 Average judgment offered by jury for the comparison of sound pairs.

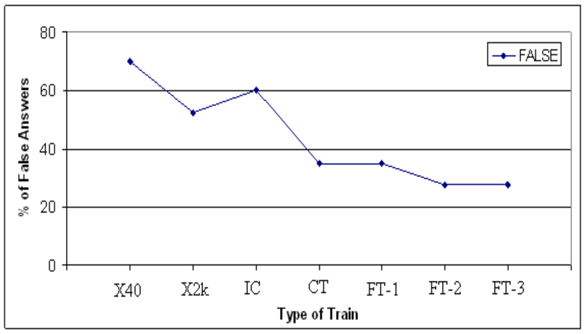

Figure 11 Percentage of persons who gave false answer to second question

From figure 11, it can be seen that for X40, X2k and IC trains more than 50% of the jury members gave the false answer. This means that more than 50% of the jury was unable to distinguish between the original and synthesized sound. They felt that the synthesized sounds were the more realistic sound. For CT train more than 30% of the jury offered false answers and for three fragments of the freight train this percentage varies from 20% to 30%. From the above discussion and the judgments shown in figure 12 it can be said that the results of the synthesized sound for the trains X40, X2k, IC and CT are satisfactory. However synthesis of freight train sound needs further modifications to represent it more realistically. Hence, only the sounds of first four trains are considered for the further work.

5.2 Creation of Virtual Railway Sounds for Pleasantness (Second Listening Test)

Fifteen different combinations of different modifications on different trains were tried.

These combinations are given in Table 1.

Table 1 Different combinations used to create virtual pleasant railway sound.

No.	Different combinations used	Types of train	Number given
1	Broadband noise: - 5dB	X2k, IC, X40, CT	1, 2, 3,4
2	Broadband noise: - 8dB	X2k, IC, X40, CT	9,8,6,15
3	Rolling + Broadband noise: 5dB	X2k, CT	5, 13
4	Rolling + Broadband noise: - 8dB	X2k, IC, CT	12,14, 7
5	Tone + Broadband noise: - 8dB	X40	11
6	Rolling noise: - 5dB	CT	10

Second listening test was performed to compare the above mentioned virtual railway sounds with the reference sound. Each member was asked to listen to the sounds carefully and was asked to compare the sounds on the pleasantness scale of -3 to +3. This scale was explained as: -3 = much more unpleasant compared to the reference sound, 0 = equally pleasant as the reference sound and +3 = much more pleasant compared to the reference sound.

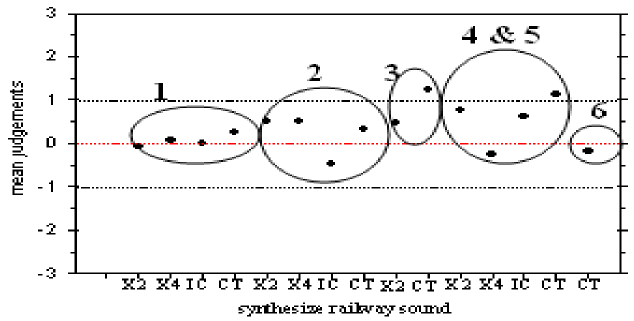

Figure 12 Mean judgments offered by the jury members for the pleasantness of different synthesized sound

Reduction of only broadband noise by 5 dB did not improve the score of pleasantness to an appreciable extent. When the broadband noise was reduced by 8 dB the scores for all trains except for IC train get improved for pleasantness. When the rolling noise and broadband noise together were reduced by 5 dB then the pleasantness of the railway sound improved somewhat. Pleasantness of the total produced railway sound was further improved by reducing the rolling and broadband noise by 8 dB. By reducing only the rolling noise of commuter train (CT) the sound became slightly unpleasant.

6 Conclusion

From the first listening test for validation of sound, it can be concluded that the synthesized sounds of trains X2k, X40, IC and CT are sufficiently validated. From the judgments offered by the jury to the sound of Freight train, it can be concluded that some more research is needed to synthesize this sound adequately. Hence, it can be said that the synthesis of the train sound with the current model is possible only for the passenger trains.

From the second listening test of comparison of synthesized sounds as a function of pleasantness, conclusions can be drawn that broadband noise along with rolling noise tones have a clear influence on the pleasantness of the sound. It can be seen from the judgments offered by jury to different combinations of sound components that reduction of only broadband noise or only rolling noise is not sufficient to improve the pleasantness of the sound. It is interesting that the reduction of only broadband noise in IC train affected adversely on the pleasantness of the sound. This is because the rolling noise tones are one of the major sources of total produced noise of IC train. The broadband noise has the masking effect on these rolling noise tones. The reduction of the broadband noise limits the masking effect of the broadband noise and leads to more annoyance. It can also be seen from the judgment offered by the jury that when the broadband noise along with the rolling tones are reduced, the pleasantness of the sound increases for all trains except X40.

Acknowledgement

The authors gratefully acknowledge the funds provided by European Commission, Asia Link-ASIE/2005/111000 and Swedish International Development Agency to carryout this work.

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