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ASSESSMENT OF THE ACOUSTICAL COMFORT IN HIGH-SPEED TRAINS AT THE SNCF: INTEGRATION OF SUBJECTIVE PARAMETERS

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In order to understand better passenger perception, SNCF has recently begun new acoustics research. Usually, the acoustic comfort in high-speed train coaches is evaluated using the A-weighted sound pressure level. However, a preliminary psychoacoustic study has pointed out that this unit may not be the most appropriate one and that subjective factors have to be considered. To determine the most important parameters involved in the acoustic annoyance and the most appropriate unit, a new research programme has been planned.

1. INTRODUCTION

The two major aspects of the acoustic comfort studies carried out at the SNCF are:

- on the commercial side, the company has to satisfy the customer's need for comfort,
- on the technical side, improvements must be done to minimize the annoyance due to the increase of train speed.

The importance of these tasks has led the SNCF to act in order to improve comfort in its trains, and especially to study the relevant acoustical aspects.

For many years, the acoustic comfort inside trains was characterized by physical parameters such as the sound pressure level (S.P.L.) and the noise reduction (N.R.) which can be easily measured and compared. They were determined from vibroacoustic measurements within prototypes or coaches in service (moving or motionless). The information on dynamic behaviour of high-speed trains is thus essentially empirical, and provides useful information to identify the main

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mechanisms that generate noise in rolling stock. However, the complex fluid–structure interaction involved is not fully characterized and understood. This experimental approach enables acoustic comfort to be optimized in current trains. Unfortunately, this method does not evaluate the acoustic quality when future trains are being designed. Hence, a simulation tool is necessary to include the acoustical constraints in order to specify the characteristics of new rolling stock. In addition, this modelling technique will enable improvements to be made to existing trains. Therefore, two different numerical models have been developed for TGV Duplex coaches. The first one is based on a semi-analytical modal superposition method and is used in the low-frequency range. The second one uses statistical energy analysis (SEA) to analyze the high frequencies. As it appears difficult to obtain an accurate prediction when considering the complexity of the system, the goals of these simulation tools are restricted to the understanding of the physical phenomena which generate the acoustic field within the coaches. In other words, this modelling technique includes the simulation of the coach excitation in normal operating conditions and the characterization of the energy path through the structure. The numerical results have shown that such simplified models are efficient.

Consequently, it has been decided to combine measurements and numerical modelling in order to enhance understanding of acoustic comfort in high-speed trains. Experimental data are fed into the models in order to validate the models. Using this method, aerodynamic and acoustic excitations are well characterized and the energy path through the coach structure roughly identified. The main aspects of the acoustic pressure spectrum can also be predicted on both floors of the Duplex coaches.

Actually, this "physical" approach seems to be somewhat restrictive. Indeed, the psychoacoustic study discussed later has highlighted the fact that the acoustic comfort of passengers could not be evaluated using only physics parameters. The individual customer's expectations and the conditions on board must be considered. The research programme, briefly discussed in the last part of this paper will take into account these two aspects.

2. THE SUBJECTIVE FACTORS

Two listening tests were conducted in the laboratory with a two-fold purpose. Firstly, the relevance of the A-weighted SPL, which is used as an acoustic comfort indicator, is analyzed. Secondly, the notion of a spatial global level is investigated.

2.1. ACOUSTIC CHARACTERISTICS

Acoustic samples were recorded in the first coach of a Duplex TGV running at 300 km/h on a straight line (tunnels and noise barriers were not present). A dummy acoustic head (Brüel & Kjaer 4100 and 2672) and a digital recorder (DAT) were used to obtain binaural samples for some seats within the coach (see Figure 1). All the signals were equalized in order to be listened with headphones (Sennheiser

Figure 1. The acoustic head in the first floor of TGV Duplex.

HD580). Software has been developed to ensure that the test is similar for each candidate; acoustics samples were played by the computer through the headphones with a calibrated level. Responses were automatically recorded.

Using the first listening test, the relevance of the A-weighted SPL as a comfort indicator was analyzed. Seven acoustic samples were classified by listeners on a continuous scale from the least to the most pleasant. All signals were constructed using the original samples recorded at the middle of the lower floor of a Duplex TGV (seat BTC in Figure 2). The original data power spectral density is illustrated in Figure 3.

This spectrum shape is representative of the noise in a coach. Most of the energy is concentrated between 0 and 1000 Hz and some peaks can be noted at 139, 300 and 800 Hz. Considering the information available on the source of the noise with respect to the frequency, the original signal has been filtered in order to create the other samples:

- F139, original signal for which the 139 Hz pure tone is removed,
- F300, original signal for which the 300 Hz pure tone is removed,
- F800, original signal for which the 800 Hz pure tone is removed,
- FBF, original signal where the level is attenuated by around 6 dB between 0 and 139 Hz,
- FMF, original signal where the level is attenuated by around 6 dB between 139 and 1000 Hz,

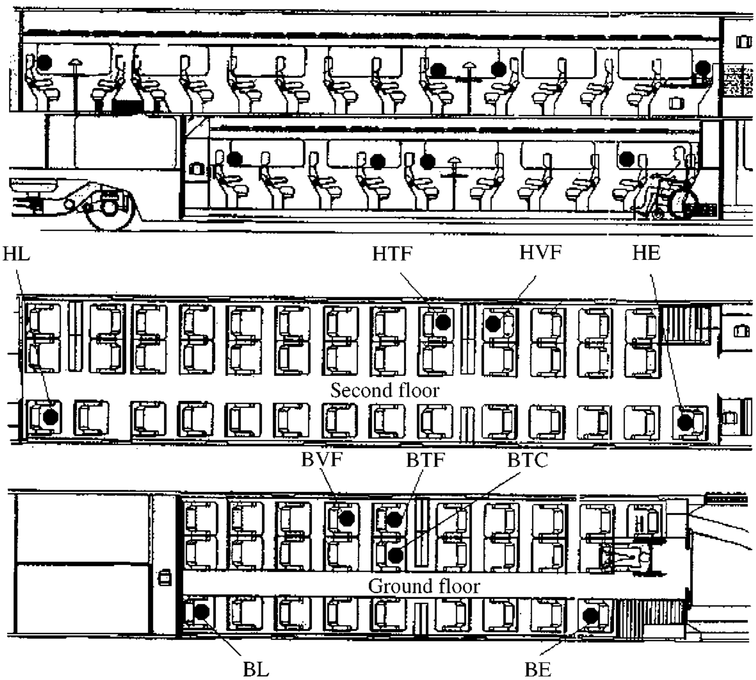

Figure 2. The measurement positions of the acoustic head.

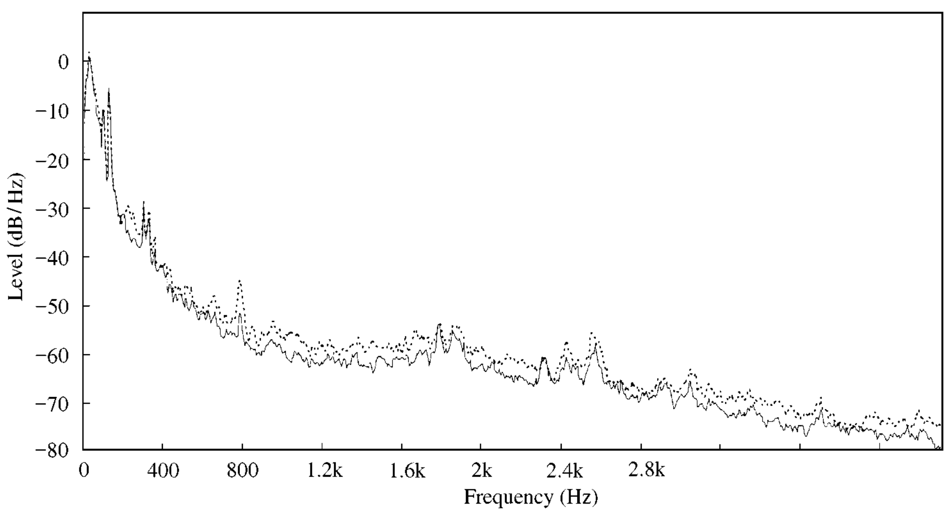

Figure 3. The power spectral density of the acoustic signal of the right ear (solid line) and the left one (dashed line).

- FHF, original signal where the level is attenuated by around 6 dB between 1000 and 4000 Hz,

The SPL of filtered signals was between 1 and 3 dBA lower than the original level.

Using the graphical interface, the listener was able to listen the acoustic samples and to classify them on an increasing scale of pleasantness.

The second test was used to verify the homogeneity of the sound. Sixteen samples were recorded at different seats in the TGV Duplex. Although the measurement positions were different (see Figure 2), the A-weighted SPL was almost constant. A dominance test was performed: subjects listened to pairs of acoustic samples and chose, for each pair, the more pleasant sound. These pairs were presented in a random order.

2.2. RESULTS

Forty-three persons (24 men and 19 women) were subjected to both tests. At the end of the test an open question about the test itself was asked. Listeners used the graphical interface without any problem but it appeared that 36 min was a maximum test duration. Moreover, the first test seemed to be easier than the second one.

The analysis of the answers of the first test was performed with a direct method. The mean of the pleasantness of each acoustic sample was calculated according to the classifications made by the listeners. Results are illustrated in Figure 4.

The wide band filtered signals (FBF and FMF) were more pleasant than F300 and F800 sounds. In fact, the attenuated signals in the frequency bands 0–139 and 139–1000 Hz were the most pleasant. The acoustic energy in these frequency bands appears to influence pleasantness for the passenger. Despite the difference between the filters bandwidths, pleasantness of signals FBF and FMF seemed to be similar.

The correlation between sound pressure levels and the pleasantness of the signals was low (correlation coefficient = 0·44). Figure 5 shows that, although F300 and FHF have got about the same A-weighted SPL, their corresponding pleasantness were very different.

This listening test has shown that passengers are most sensitive to the energy inside the frequency band 0–1000 Hz. However, the A-weighted SPL attenuates this part of the spectrum. Thus, the A-weighted SPL may not be the most appropriate indicator of the acoustic comfort in trains: others criteria should be considered.

In the second listening test, the Bradley Terry Luce [1] algorithm has been used to classify acoustic samples from the least to the most pleasant and the classification has been validated with the bootstrap method [2]. Listener's answers to the pairs (A, B) and (B, A) have shown that 79% of the choices was coherent. Some differences have been detected by candidates even if the level in dBA remained low and constant. The classification of different seats shown in Figure 6 is relevant: the acoustic sensation is more pleasant from one extremity to the other

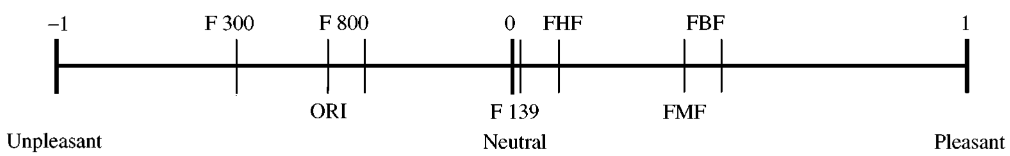

Figure 4. The pleasantness (mean values) of acoustic samples of the first test.

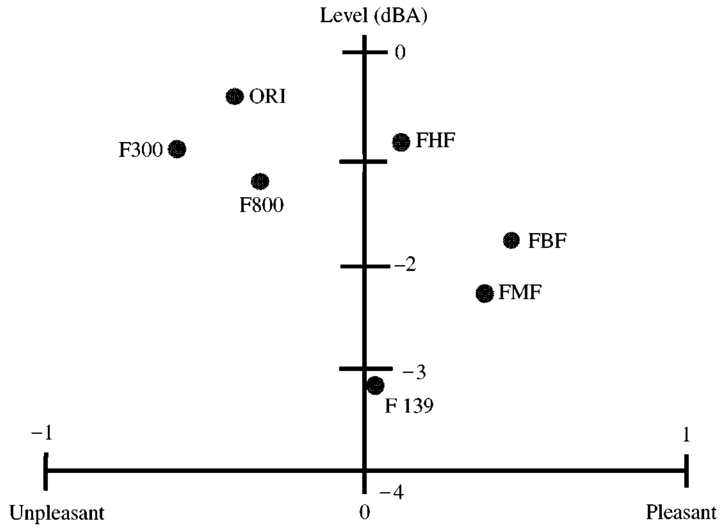

Figure 5. The acoustic samples in the train (pleasantness, level in dBA).

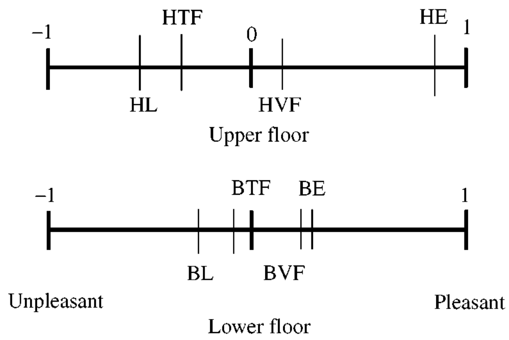

Figure 6. The pleasantness (mean values) of acoustic samples of the second test.

one. The acoustic surroundings near windows are more pleasant than those between windows. The similarity of the pleasantness of the acoustic samples is greater in the lower floor than in the upper floor.

This test has shown that despite the low A-weighted SPL existing within a coach of the TGV Duplex, the acoustic sensation is not homogeneous in both floors. Acoustic ambience for seats near windows is more pleasant, and this pleasantness increases from one extremity of the coach to the other.

Finally, tests results confirm that the acoustic comfort in TGV depends on several subjective factors but that simple psychoacoustic studies will answer some specific questions. The results have limitations because listening tests in laboratory do not represent real situations. Finally, test analyses show that experience is required to interpret results correctly. Work in collaboration with psychoacoustic specialists is thus essential to investigate this subject further.

3. THE NEW RESEARCH PROGRAMME

The tests results discussed above have led SNCF to conduct a further acoustic comfort study of passenger annoyance due to low-frequency phenomena. The two main aspects of this project are:

- improving the characterization of low-frequencies sources,
- developing an acoustic comfort indicator that will allow a more precise evaluation of passenger annoyance.

The development of an acoustic comfort indicator requires representative modelling of passenger perception. Collaboration between acousticians and social scientists is needed to develop a correlation method between passenger annoyance and physical parameters. The SNCF research department has developed a partnership with two French research teams from the Laboratoire d'Acoustique Musicale and the Laboratoire Languages, Cognitions, Pratique et Ergonomie. The main tasks of this 3 year project are:

- Firstly, a survey will be conducted using a panel of passengers during a trip by train. The answers will be analyzed using a linguistic and cognitive method which has been validated by the partners. The purpose of this analysis is to assess the degree of importance of the acoustic comfort in comparison with other internal environmental factors. Simultaneously, measurements will be taken to characterize the physical parameters (temperature, luminosity, acceleration, etc.) during the trip in the TGV coach. From the analysis of the data, the relevant physics parameters will then be selected.
- Secondly, a listening test using binaural signals recorded in the trains and modified with respect to the previous cognitive study will be performed. This test will allow the development of a simulator in which different stimuli related to the comfort will be reproduced. Then, following analysis of the passengers' answers to this listening test, a group of people will be trained to evaluate the acoustic comfort.
- Finally, when submitted to tests in the simulator, the group of trained people are expected to represent passengers' feelings about the acoustic comfort. Therefore, their assessment could be used to define an annoyance indicator.

4. CONCLUSION

The SNCF research on acoustic comfort is currently concentrated on the passenger perception. From the initial psychoacoustic study, it was decided to initiate an ambitious project aimed at the characterization of acoustic annoyance in trains. The project is expected to provide information that will allow a better acoustic specification of future rolling stock and also to enhance passenger comfort.

Other criteria involved in the global comfort sensation perceived by passengers are also to be studied at the SNCF.

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