

## TRADE-OFF APPROACHES FOR THE VIBROACOUSTIC ANALYSIS OF TRAINS

F. Sorribes-Palmer\*<sup>1</sup>, M. Ghaemi-Nasab<sup>1</sup>, M. Chimeno<sup>2</sup>, G. Alonso<sup>1</sup>

<sup>1</sup>IDR/UPM, E.T.S.I. Aeronáuticos, Universidad Politécnica de Madrid, Madrid, Spain  
{felix.sorribes, m.ghaemi, gustavo.alonso}@upm.es

<sup>2</sup>UPM, E.T.S.I. Aeronáuticos, Universidad Politécnica de Madrid, Madrid, Spain  
marcos.chimeno@upm.es

**Keywords:** FEM, BEM, SEA, Trains, Vibroacoustic, Interior Noise Prediction.

**Abstract.** *Passengers' comfort in terms of acoustic noise levels is a key design driver for train design. The problem is especially relevant for high speed trains, where the aerodynamic induced noise is dominant, but it is also important for medium speed trains where the mechanical sources of noise may have more influence.*

*The numerical interior noise prediction inside the train is a very complex problem, involving many different parameters: complex geometries and materials, different noise sources, complex interactions among those sources, broad range of frequencies where the phenomenon is important, etc.*

*In this paper, the main findings of this work developed at IDR/UPM (Instituto de Microgravedad "Ignacio Da Riva", Universidad Politécnica de Madrid) are presented, concentrating on the different modelling methodologies used for the different frequency ranges of interest, from FEM-BEM models, hybrid FEM-SEA to pure SEA models. The advantages and disadvantages of the different approaches are summarized. Different modelling techniques have also been evaluated and compared, taking into account the various and specific geometrical configurations typical in this type of structures, and the material properties used in the models.*

*The critical configuration of the train inside a tunnel is studied in order to evaluate the external loads due to noise sources of the train. In this work, a SEA-model composed by periodic characteristic sections of a high speed train is analysed inside a tunnel.*

## 1 INTRODUCTION

Noise prediction inside vehicles is a problem in which industry is still working on, in the middle and high frequency ranges Statistical Energy Analysis method (SEA), (Lyon 1995) and combination with finite elements FE method (hybrid FE-SEA) are widely used by automobile, rail and aerospace industries [ (Charpentier 2004), (Moeller 2010)].

A considerable effort has been done in rail industry along the last years to characterize the noise sources [ (A. Lauterbach 2010), (Hardy 1977)], the acoustic behavior of the structural parts [ (Kohrs 2009), (Xie 2006) ], noise transmission [ (Orrenius 2009), (A. Vallespín 2011)], and to optimize the noise control treatments in order to reduce the sound pressure level and increase the comfort of the passenger [ (Forssén 2011), (Choi 2004), (Jové 2009)].

In this work, simplified models (FE-BEM, FE-SEA and SEA) of a characteristic section of a high speed train have been developed in order to predict the interior noise inside the train in all the frequency range without analyzing the whole train. A model of 50.6 m of train composed 23 sections of 2.2 m length along the longitudinal axis of the train has been studied.

The idea of this method is to divide the train in characteristic sections and compose them in order to build up different configurations of a train, and analyze them to obtain optimized trimmings along the train.

This section approach has been applied to the prediction of interior noise in two scenarios. First, an open field scenario is studied for the whole frequency range developing FE-BEM, FE-SEA and SEA models.

The second scenario considered is the pass through a tunnel. For this scenario the aim is to analyze the influence of far train's acoustic loads in the studied section. The analysis is performed through a SEA model for the train and the air inside the tunnel

In (Choi 2004) sound pressure level measurements in the interior of a train inside a tunnel at the speed of 295 km/h are presented noise level ranges from 72 to 82 dB(A) The noise level in case of slab track is larger in 5 dB(A) than the one of ballast track, this indicates that ground absorption must be considered in the models inside the tunnel.

In this work a summary of the investigation process carried out in order to predict noise inside and outside a train, to design optimized noise control treatments to achieve high quality comfort levels, is presented.

## 2 MODELS AND CONFIGURATION

### 2.1 Introduction

In this work we show that modelling a characteristic section of a wagon with an equivalent structural and acoustic behaviour is enough to analyse in the first steps of the design of a new train: the efficiency of the noise control treatments (NCT). Solving one wagon (FEM-BEM model) till 100 Hz would take weeks in a normal PC. With this methodology the analysis at high frequencies can be done without simulating the whole wagon.

### 2.2 Structural and fluid model

The section under study is at 23 meters from the nose of the train was generated based on typical high speed train structure, with extruded (truss-like cores) and ribbed panels, derived from the examples found in the bibliography.

The model is separated in parts with similar structural properties; a modal analysis was done to identify the subsystem partitions for SEA modelling. The truss-like cores that com-

pose the structural box were separated in external, core and internal subsystems to facilitate the separation of interior and exterior domains and to make easier the connection to the exterior air.

Open field models for low, middle and high frequencies were developed (see figures 1,2 and 3 respectively). External elements as the bogie and the cavity down the train wagon simulate the bogie or the equipment's departments depending on the position of the section in the train. In the created models the condition of rigid walls is applied to this faces or plates (with null acceleration spectra) to decouple the motion of this system from the structural box.

The structure box is pinned and the faces in the air that delimitate the cross section of the train has been supposed as periodic (rigid wall), this approach is highly conservative as the pressure inside is over-predicted. The possible leakage through gaps in gangways on windows has been neglected. The NTC's are connected to the structural box by point junctions. In the tunnel scenario the ground has an absorption coefficient due to the ballast track, the value of 5% was assumed.

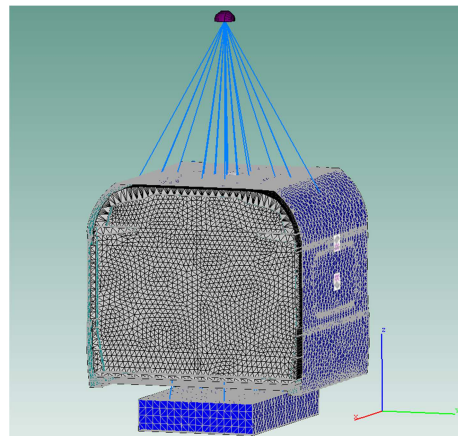


Figure 1: FEM-BEM open field model.

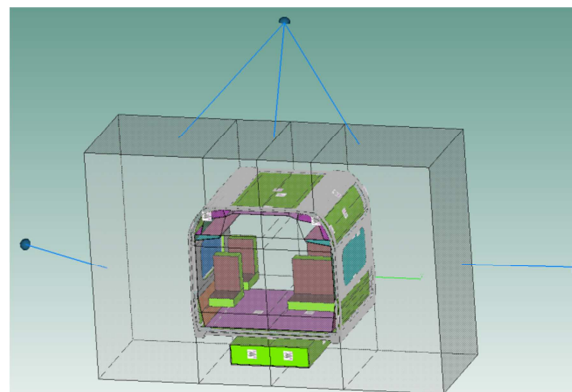


Figure 2: FEM-SEA open field model.

In the hybrid model the FE structures are substituted by equivalent SEA plates in which the modal density  $n(w)$ , damping loss factor (DLF) and the coupling loss factor (CLF) between the plate and the acoustic cavities have been modified.

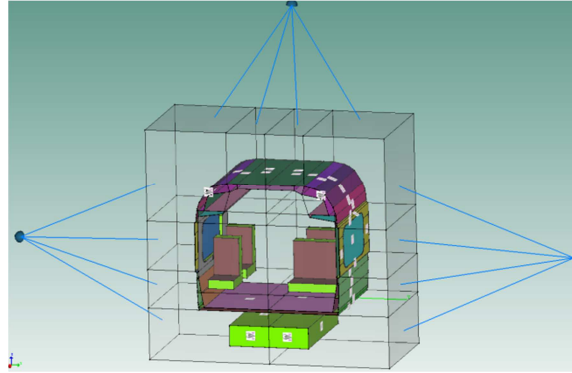


Figure 3: SEA open field model.

For the case with the train inside a one track tunnel two models were created, a model to simulate the first 2 wagons, composed by 23 sections, in which 9 sections are in front of the noted section at 23 meters from the nose and 13 sections at the back of this section (figure 4a) and another one of the characteristic section located at 23 meter from the nose of the train (figure 4 b).

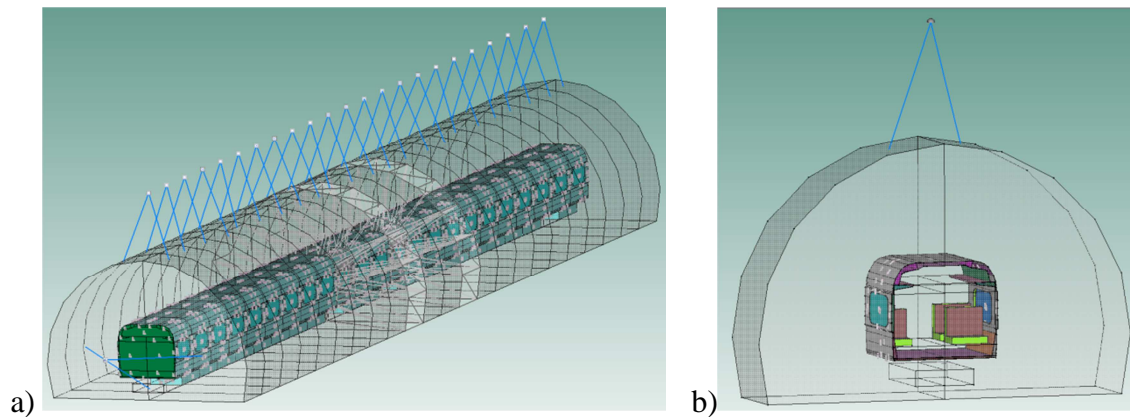


Figure 4: a) 2 wagons SEA model inside the tunnel the sections highlighted are at 23 and 29 meters from the nose of the train b) SEA model section at 23 meters from the nose of the train.

The modal densities, damping loss factors, and coupling loss factors of the SEA equivalent plates in the hybrid FE-SEA model were obtained from the analysis of the FE model. The number of modes per frequency band in 1/3 of octave in the SEA plates was higher than 3 modes in the frequency range under study. The known transmission loss (TL) of similar subsystems found in the bibliography was applied in the area junctions.

### 1.1 Loads

The structure and air borne loads that have more relevant influence in the interior noise of a high speed train are: turbulent boundary layer (TBL), equipment noise (air-conditioning and ventilation systems), bogie, engine, converter, inverter, chopper, wheel-rail noise, pantograph, air gap between cars, etc... Within this work only loads with experimental data obtained from the bibliography were considered: inverter, converter, and chopper.

The power injection,  $P_i$ , from the bogie in the floor, and the HVAC in the roof were calculated from theoretical formulation, analyzing the mobility,  $Y$ , in the points of connection of the bogie and the HVAC with the structural box with a FE model of the subsystem, and using typical accelerations,  $a$ , found in the open literature to obtain the velocity.

$$P_i = \frac{1}{2} \frac{\langle v \rangle^2}{Y}$$

The airborne loads are shown in figure 5, the power injection from the roof and floor are shown in figure 6 and the load due to the turbulent boundary layer (TBL) is calculated with the model proposed by (Cockburn 1974), the SPL generated by the TBL in a plate at 23 meters from the nose of the train corresponding to a velocity of 250 km/h is shown in figure 7.

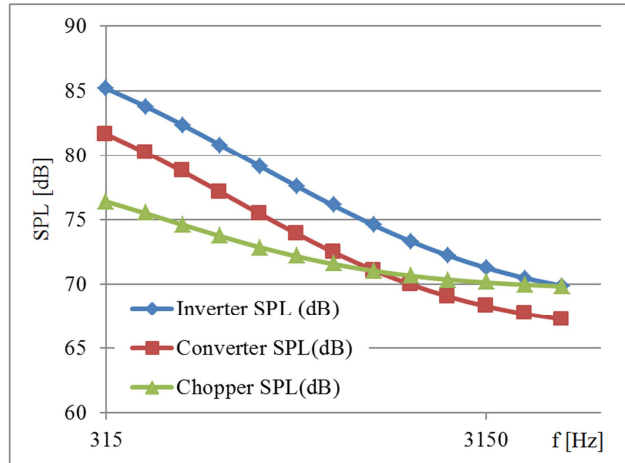


Figure 5: SPL(dB) of the converter, inverter and chopper located under the train.

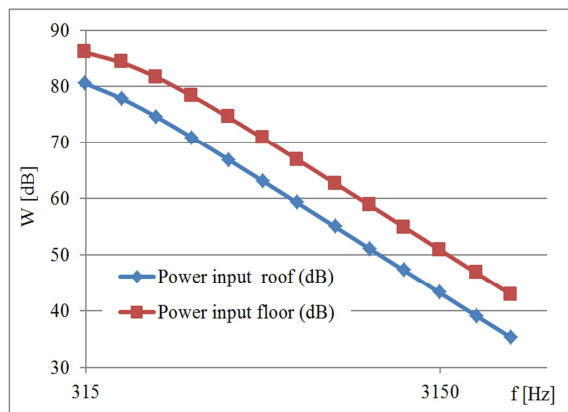


Figure 6: Power input in floor and roof deduced from the experimental data and the mobility obtained from FE analysis.

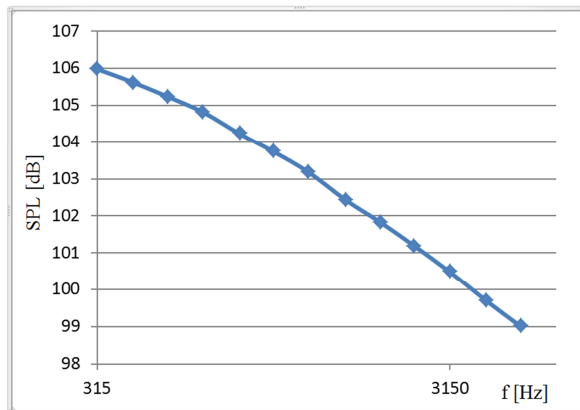


Figure 7: Theoretically derived SPL(dB) due to the TBL corresponding to a velocity of 250 km/h and at distance of 23 meters from the nose of the train.

## 2. INTERIOR NOISE PREDICTION THROUGH SECTION APPROACH

In this part a study of the continuity in the results obtains with the 3 vibroacoustic models is done. The high frequency model SEA is used to predict the interior noise at a 295 and 350 km/h in open field scenario.

### 2.1 Models continuity

In the experimental measurements in open field the pressure inside the train was recorded with several microphones inside the selected section under study, located at 23 meters from the nose of the train. The SPL of the microphones were used to correlate the vibroacoustic models comparing the SPL averaged in the interior acoustic cavities that simulates the air volume measured with the microphones.

Under 160 Hz some acoustic modes appear in the cavities and a resonant behaviour appear in the air inside the train, this results are not in agreement with reality, due to the fact that the simulated volume is smaller than the actual one.

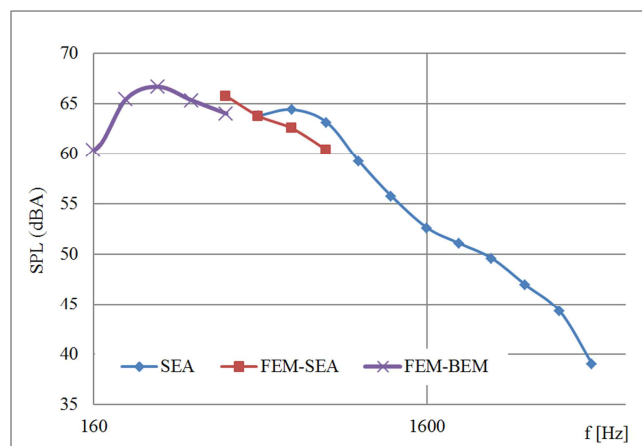


Figure 8: SPL (dBA) predicted numerically inside the train at 295 km/h at the section 23 m.

In the figure 9 can be appreciated that there is continuity between the vibroacoustic models.

### 2.2 Interior noise prediction for higher velocities (350 km/h)

To simulations in open field at 295 and 350 km/h are done to show the influence of the speed of the train in the SPL spectra. The prediction of the interior noise and the experimental results are compared in figure 13.

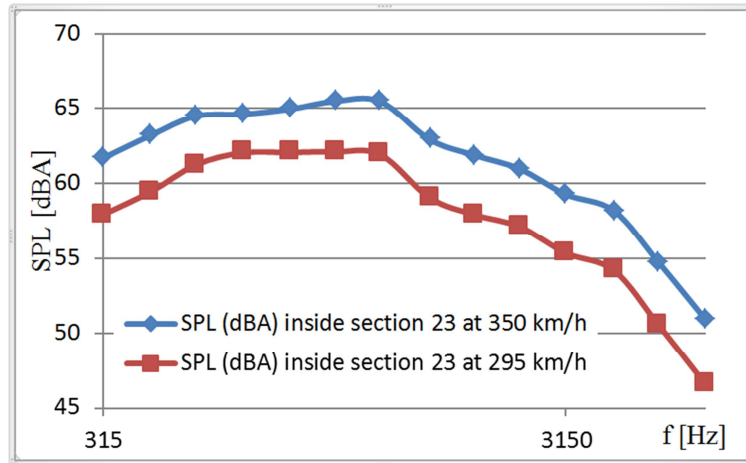


Figure 9: SPL (dBA) predicted inside the train at 295 and 350 km/h at the section  $x=23$  m with the section approach.

### 3. AIRBORNE NOISE SOURCES TRANSLATION

Once the models shown continuity, the SEA model was used to evaluate the effect of the loads that were not considered in the models. For this study a model with the train inside a tunnel was created, composed by 23 characteristic sections, simulating the first two wagons. Applying the corresponding TBL in the SEA exterior plates of the wagons and the SPL of the converter at section 29 m from the nose of the train. The SPL in the exterior acoustic cavity in the section under study (at 23 m from the nose of the train) is used as target spectra in the model of just one section considering then only an equivalent external acoustic load, which takes already into account the attenuation and directivity in the tunnel.

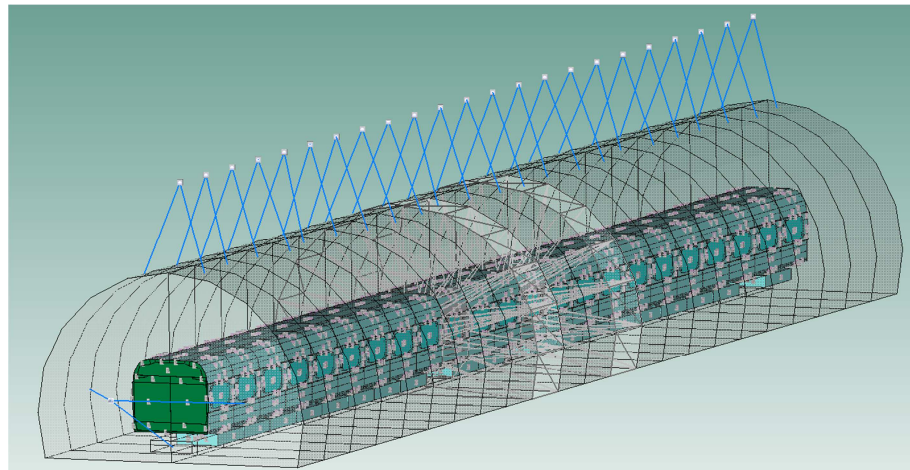


Figure 10: SEA model inside the tunnel composed by 23 characteristic sections.

In figure 11 the attenuation of the acoustic load through the tunnel can be appreciated. It can be seen that the influence of the airborne sources is small; especially at high frequencies (over 1000 Hz) the difference is lower than 0.2 dB.

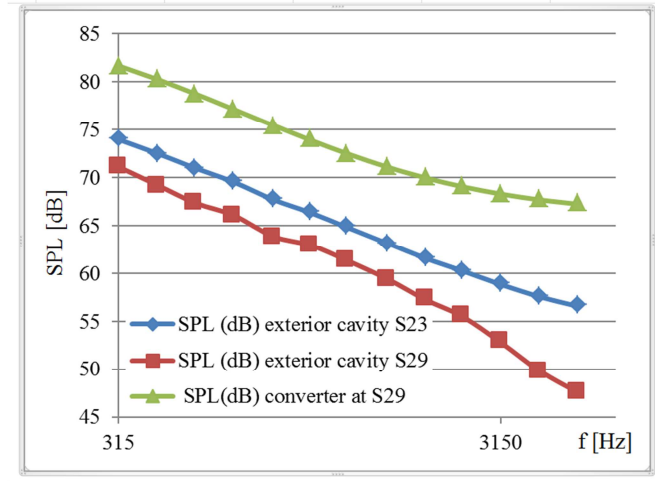


Figure 11: SPL (dB) of the converter at section 29 m (triangles), SPL (dB) predicted numerically with the 2 wagons model at the exterior acoustic cavity due to the noise generated by the TBL in the whole train and the converter in the section 23 m (squares) and in the section 29 m (rhombi).

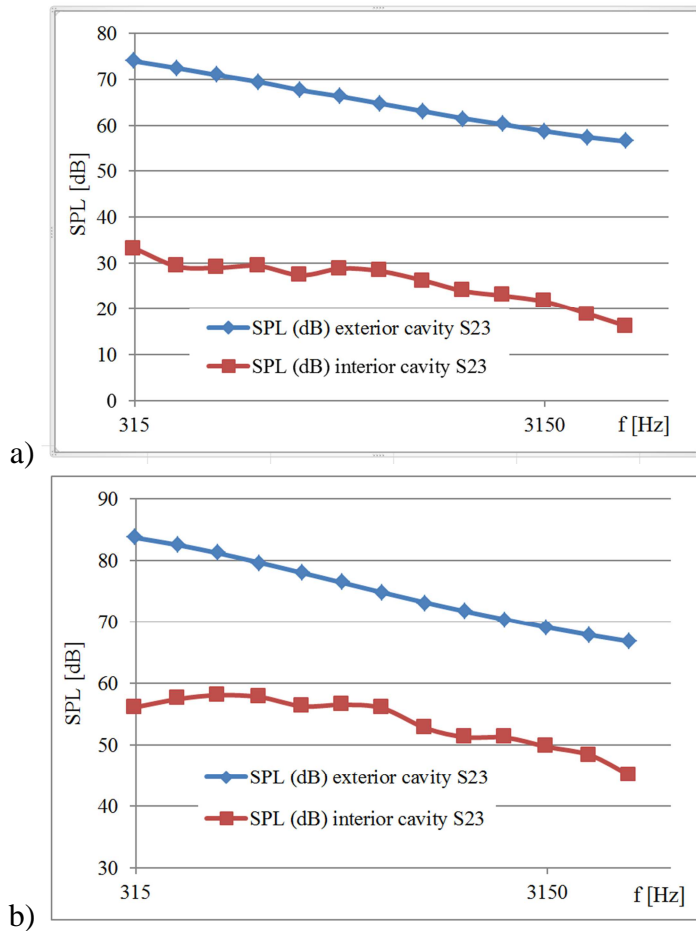


Figure 12: a) SPL (dB) predicted numerically with the one section model in the interior and exterior acoustic cavity in 23 m from the nose of the train, due to the relocated load of converter at 29 m and TBL of the whole train b) SPL (dB) in the interior and exterior of the section at 23 m, due to all the loads in this section and the relocated loads of the converter at 29 m and the TBL of the rest of the train.



## 4. CONCLUSIONS

- A new procedure to analyze interior noise in trains has been presented.
- With this section approach the vibroacoustic models developed for whole frequency range show continuity. A better characterization of the loads, and the structures (mobility at the excitation points, damping loss factors, coupling loss factor, power injection measurement) would be needed to increase the accuracy of the interior noise predictions.
- Based on this section approach method a procedure to derive loads far from the section under study is presented for the train inside the tunnel scenario.
- Translation of structural loads is feasible through the same procedure although is beyond the scope of this study.

## ACKNOWLEDGEMENTS

The authors want to thank to UPM for the scholarship, and the aids to do short visits at TU Berlin to improve the knowledge of the different technics to analysis vibroacoustis. Authors wish to thank Dr. Jesús López Díez, sadly passed away during the preparation of this work, for his helpful discussions and inspiration.

## REFERENCES

- [1] A. Lauterbach, K. Ehrenfried, S. Kröber, T. Ahlefeldt and S. Loose. Microphone array measurements on high-speed trains in wind tunnels. *Berlin Beamforming Conference*. 2010.
- [2] A. Vallespín, O. Gibert, J. Sapena, J. Jové, F. Guerville and N. Cuny. Passanger door Transmission Loss improvement in a train using a vibro-acoustic numerical model combining deterministic and statistical techniques. *inter-noise*. 2011.
- [3] Charpentier, A., Blanchet, D. and Fukui, K. Full vehicle SEA model uses detailed sound package definition to predict driver's headspace acoustic response. *inter-noise*. Prague, 2004.
- [4] Chen, S.M., Wang, D.F. and Zan, J.M. Interior Noise Prediction of the Automobile Based on Hybrid FE-SEA Methods. *Mathematical Problems in Engineering*, 2011.
- [5] Choi, S., Lee, C.W. and Kim, J. C. Interior noise of a korean high-speed train in tunnels. *ACOUSTICS*. Gold Coast, Australia, 2004.
- [6] Dupal, J. and Králíček, J. Vibroacoustical analysis of rail vehicle. *Applied and Computational Mechanics*, 2007.
- [7] Forssén, J., Stefan, T., Corakci, A. C., Frid, A. and Kropp, W. Modelling the interior sound field of a railway vehicle using statistical. *Applied Acoustics*, 2011.
- [8] Hardy, P.W. Eade and A. E. Railway vehicle internal noise. *Journal of Sound and Vibration*, 1977.
- [9] Jové, J., Sapena, J., Guerville, F. and Blanchet, D. Interior structure borne noise prediction of the cabin of a high speed train using FE-SEA hybrid methods. *inter-noise*. Ottawa, 2009.

- [10] Kohrs, T. and Petersson, B. A. T. Wave beaming and wave propagation in light weight plates with truss-like cores. *Journal of Sound and Vibration*, 2009.
- [11] Lyon, R. H. and DeJong, R. G. *Theory and Application of Statistical Energy Analysis*. Butterworth-Heinemann, 1995.
- [12] Moeller, M. J., and Barker, G.M. Modeling freighter aircraft interior noise. *Noise-Con*. 2010.
- [13] Orrenius, U., Cotoni, V. and Wareing, A. Analysis of sound transmission through periodic structures typical for railway carriages and aircraft fuselages. *Noise and Vibration: Emerging Methods*. Oxford, 2009.
- [14] Priebisch, N. and Lalor, H. The prediction of low- and mid-frequency internal road vehicle noise: a literature survey. *Proceedings of the IMechE, Part D: Journal of Automobile Engineering*, 2007.
- [14] Xie, G., Thompson, D.J. and Jones, C.J.C. A modelling approach for the vibroacoustic behaviour of aluminium extrusions used in railway vehicles. *Journal of Sound and Vibration*, 2006.