FEM ANALYSIS OF THE INTERNAL ACOUSTICS OF A RAILWAY VEHICLE AND ITS IMPROVEMENTS

Andrea Bracciali
Dipartimento di Meccanica e Tecnologie Industriali
Università degli Studi di Firenze
via Santa Marta 3, 50139 Firenze, Italy
Tel. +39 55 4796395 - Fax +39 55 4796400
e-mail: bracciali@ing.unifi.it

Carlo Pellegrini
Breda Costruzioni Ferroviarie S.p.A.
via Ciliegiole 110b, 51100 Pistoia, Italy
Tel. +39 573 370276 - Fax +39 573 370292

SUMMARY

Railway coaches internal acoustics is a topic still partially unexplored even if its importance is clear for passengers comfort. In this work a finite element acoustic model is built and compared to noise measurements performed during test runs on a 2nd class coach of the FS ETRY500 train running at 250 km/h on an outdoor ballasted track.
Fundamental acoustical data for model set up, such as absorption coefficient at different frequencies and for several configurations of the coach, were available from a previous experimental analysis.
The model was used to evaluate the efficiency of structural/acoustical modifications on sound pressure level heard by passengers. Obtained results provide interesting guidelines for transmission path indentification on actual coaches and for the development of effective solutions on new coaches.

Keywords
Railway coach internal acoustics, FEM acoustic analysis, simulation, noise, comfort

INTRODUCTION

During the last few years the number of scientific papers and norms concerning railway noise increased enormously. The main problem is the noise pollution towards people that live aside the railway lines, as this is in practice the only direct consequence on the enviroment if the exhaust gases of Diesel engines, that moreover are not very used in Italy, are neglected. Contrary to what happens for both the motor and flight-fields, the number of publications regarding the combined acoustic-structural analysis of coaches, especially referring to the inside acoustics, is practically null.

Even if the actual trend for modern high speed trains is to desing coaches that are particularly insensitive to pressure drops and consequently are almost sealed, the internal noise inside them does not disappear, as it enters the passenger area thanks to the acoustic transmissibility of the structure of the coach.

The designer of passenger rolling stocks has remarkable, if not even insuperable, difficulties in choosing materials and forms of the components that the train is formed of in order to reduce the internal noise. As almost all the coaches are built today without internal compartments, according to the saloon configuration, it is clear that the internal acoustics becomes a critical factor as geometrical dimensions can originate resonances at very low frequencies (about some ten Hz).

A complete design analysis of a closed space of this kind is simply impossible, as the approximations made in the model (due to the inevitably inadequate detail level) and the uncertainty of some fundamental parameters, as the system entering noise, lead to certainly not very steady and indicative estimations.

The acoustic analysis carried out on a simple bidimensional model of a railway vehicle through the use of a finite element code is shown in this study. The model requires as input data the sound pressure levels measured in some points inside and outside the vehicle during tests carried out under normal running operation conditions. The aim of this research is twofold:

1.it allows the identification of main noise transmission paths from the rolling noise source to vestibule and saloon passenger areas;

2.it allows the estimation of the validity of potential improvements in the structural/acoustical properties of the coach body or linings.

After a tuning phase that led to an acceptable agreement between measured and computed values for internal SPL levels, many structural and acoustical modifications were simulated that provide useful information for the design of new rolling stock.

MODEL INPUT DATA

The Dipartimento di Meccanica e Tecnologie Industriali of the University of Florence and Breda Costruzioni Ferroviarie jointly studied the acoustical properties of the prototype ETRY500 train. Even if the series ETR500 train is very changed acoustically, the investigations were retained interesting to establish, on a modern design vehicle, a complete procedure for the identification and the measurement of internal noise.

Reverberation time measurements were performed on several coaches, acoustically following and characterizing almost all phases of construction. From this activity the averaged absorption coefficient of the materials and components mounted in the coach were derived.

Measurement of SPL underneath the coach and inside the saloon (Corbizi Fattori, 1996) during test runs on the Arezzo-Roma section of the "Direttissima" under different running conditions (speeds in the range 100÷250 km/h, internal compartment doors closed/open, outdoor and inside tunnels, air conditioning system full power/idle/off, rails with good/bad surface roughness, etc.) were made. Measurements of noise level in the center zone of the bogie were performed by using the device developed by the authors (Bracciali, 1994, 1994a, 1997), while internal noise measurements were made with standard measuring microphones.

A complementary phase was the collection of all available information about acoustical behaviour of the components of the coach. Breda Costruzioni Ferroviarie tested in the past few years specimens of many components (floor, walls, windows, etc.) to determine their Transmission Loss properties.

FEM MODEL SETUP AND VALIDATION

The simulation of a noise field can be made through several complementary techniques, listed in increasing order of complexity and computation requirements (no attempt to give a deeper description of these methods is made here, and the reader is referred for example to Brebbia, 1995):

- image sources method, ray tracing algorithms and cone/beam/pyramid tracing algorithms, extremely valid for the estimation of sound propagation in close spaces where the noise is emitted by one or more punctual omnidirectional sources;
- boundary element method (BEM) approaches, where Helmholtz equations are numerically solved coupling the fluid with the known vibration of a surface (usually obtained through a FEM simulation);
- finite element method (FEM) approaches, where acoustical and structural elements are used to estimated both noise transmission through partitions and noise generation from vibrating surfaces.

The noise inside a railway coach is both due to a transmission mechanism (the noise underneath the floor, from the bogies areas, can enter the saloon) and to a vibration mechanism (coach surfaces, excited by vibrations transmitted by suspensions, can be good radiatiors especially at lower frequencies). A FEM model is therefore the unique possibility to correctly reproduce both the air and solid noise trasmission paths, even if some problems (requirements on computation limits and results accuracy) must be carefully considered.

To acoustically model the ETRY500 coach to investigate how external noise enters the coach, both the internal compartment and the frame structure must be described in a sufficiently correct manner. The internal compartment of a railway passenger coach is a 3D space very complicated even for saloon coaches, and a precise description of all the surfaces and the volumes is impossible. The noise frequency range to be investigated (about up to 4 kHz) requires very small elements that make it impossible to describe with sufficient precision the whole volume. The noise sources, i.e. the wheels and the track, radiate in a not completely known manner, and any very detailed description of the lower surface of the coach (the one that faces the track) is simply useless for the just mentioned source indetermination. Some parts of the coach are too complicated to be modeled in detail: for example the gangway and the auxiliary equipments zones, under the coach body

between the bogies, must be considered with equivalent properties that can either be defined on a common-sense basis or be left as convergence parameters for model validation/refinement.
From the measurement campaign described above it emerged that particularly annoying frequencies were in the 160 Hz, probably due to seat spacing resonances, and 500 Hz, for rolling noise reasons, 1/3 octave bands. Simulations shown here are relative to these frequencies, even if the model proved to be valid also at all the other frequencies.
The simulation was performed on a very schematic 2D model representing the vertical cross section of the coach on its longitudinal axis (fig. 1). Only half coach was simulated, by placing symmetry conditions both at the left and at right side; this implies that the coach is considered symmetrical (both the bogies have the same sound emission) and that the adjacent coach is perfectly equal to the studied one. The model is applicable up to un upper frequency that is influenced by the maximum element length, that should be smaller than about one tenth of the wavelength at the considered frequency (Swanson, 1995).

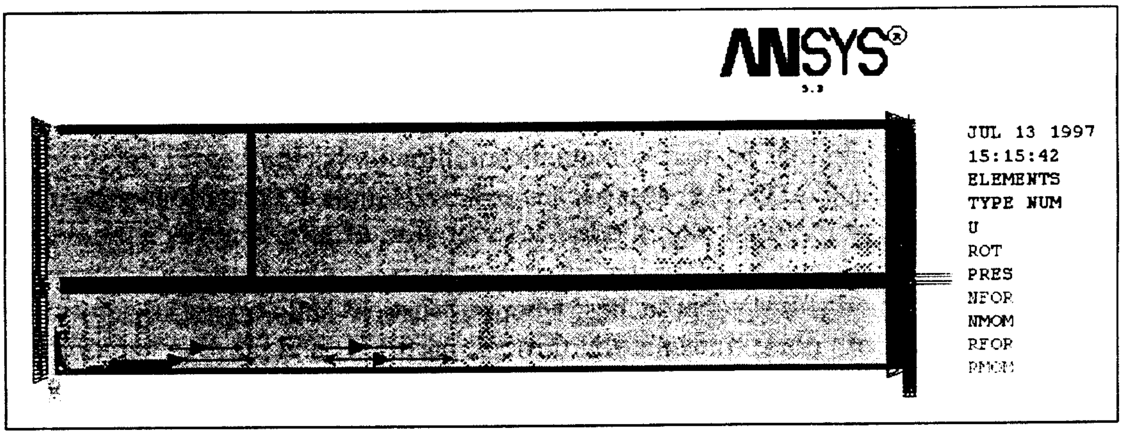

Fig. 1. Edge plot of the elements used in the FEM mesh. Indicated are also boundary conditions (symmetry conditions, monopole noise sources). Different parts of the floor were modeled with different properties.

In the area under the coach some monopole omnidirectional noise sources were placed whose strength is derived from test runs measurements. This area is delimited on the lower side by a perfectly reflecting ground, laterally by symmetry constraints and on the upper side by the floor. The number and the strength of the sources was quite arbitrary, as the exact noise distribution in the bogie area in not known. Two sources were used, one located at the wheel-rail contact point with higher strength (to take into account also the rail noise emission) and one close to the axlebox with lower strength. Their values and position were determined with a manual convergence procedure based on values measured outdoor on straight ballasted track at 250 km/h, that is actually the maximum speed for FS railway network.
The floor section above the bogie was modeled by using average mass, stiffness and geometrical properties. The floor section between the bogies is harder to model as under it the auxiliary equipments (HVAC plants, battery chargers, sealed WC plants,...) are instal-

led in shielded vanes connected to an aluminium vertical fin that runs along the coach between the bogies. The real geometry and the sound properties of these equipments are clearly too complicated to be simulated with a simplified 2D model; their effect, certainly equivalent to a higher sound absorption and impedance, was considered by increasing the density of the floor (r=450 kg/m^3 instead of the real r=275 kg/m^3) leaving the original thickness.

The central part of the partition that separates the vestibule from the saloon has a glass sliding door designed to remain close during the normal operation of the train, while lateral portions are made of layered plastic material. After a manual convergence process, optimal average simulation parameters were found. A fire resistant sliding door is present at the end of the coach, but it is normally open and it is manually closed when the coach is left alone in a yard and it is automatically closed in case of fire, and it is therefore not modeled here.

The ceiling description is not very important as, at least outdoor, the noise does not come from above the coach; a certain precision is anyway still required, as reflection properties of this component are fundamental for the final description of the sound field inside the coach. An average density of the structural aluminium sheet and of the thermoacoustic treatment was considered. Structural and geometrical properties of the elements used are summarized in table 1.

	Floor 1	Floor 2	Partition	Ceiling
Thickness (mm)	140	140	40	80
Density (kg/m^3)	275	310	300	220
Young's Modulus (N/m^2)	$7 \cdot 10^{10}$	$7 \cdot 10^{10}$	$4 \cdot 10^{10}$	$4 \cdot 10^{9}$

Tab. 1. Structural and geometrical properties of elements used in FEM ETRY500 coach simulation.

The definition of the internal volumes (shell elements of the 2D model) is different for the vestibule and the saloon, as the former is only partially empty (a relevant portion is occupied by electrical plants) while the latter is more homogeneous. In both cases the simplest description was chosen, i.e. a uniform volume. Measured absorption coefficients were applied on the boundaries of the model.

The zone that revealed to be the most critical for modeling was the gangway, both for geometrical reasons (this area is extremely complicated, and a full description is unfeasible) and for acoustical reasons (disuniformity of materials and thicknesses, rubber parts, etc., make this area more transparent to noise). As a compromise between good results and model simplicity, an equivalent defect, i.e. a 1 cm long hole in the floor near the gangway door, was used. It proved to be satisfactory as reasonably good results both in the vestibule and in the saloon areas were obtained.

The FEM model was validated at the aforementioned frequencies of 160 Hz and 500 Hz. The SPL values was computed as the average of pressure on the elements of the areas. To this goal, the saloon was divided in two areas, namely Saloon 1 and Saloon 2, that are respectively close to the partition and near the center part of the coach. A comparison between measured and estimated values is shown in Table 2, where it is possible to observe the good agreement between experimental and calculated noise levels. No estimation of the contribution to internal noise due to coach surfaces vibrations were considered in this research.

160 Hz	$\alpha_{vestibule}$=0.15 α_{saloon}=0.15 Wheel-rail contact point source strength: 106 dB Wheel web source strength: 104 dB			
	Bogie area	Vestibule	Saloon 1	Saloon 2
Measured SPL (dB)	99	76	65	64
Estimated SPL (dB)	98.4	75.9	65.1	63.8

500 Hz	$\alpha_{vestibule}$=0.20 α_{saloon}=0.40 Wheel-rail contact point source strength: 122 dB Wheel web source strength: 120 dB			
	Bogie area	Vestibule	Saloon 1	Saloon 2
Measured SPL (dB)	105	74	53	52
Estimated SPL (dB)	104.7	73.6	53.1	51.9

Tab. 2. Measurements and simulations comparison at 160 Hz and 500 Hz.

The simulation at 160 Hz led to sound pressure distributions that are very influenced by the boundary conditions as the wavelength is about 2 m, a typical vestibule dimension. Averaging the pressures in the various areas can sometimes lead to slightly unstable values. At 500 Hz the model proved to be instead extremely robust.

MODIFICATIONS PREDICTIONS

The most interesting capability of the developed model is certainly the simulation of modifications of the properties of the materials used in the construction of the coach. Several tens of simulations were performed, leading to very interesting results in terms of acoustic sensitivity, i.e. of the variation of noise levels for unitary variation of thicknesses, Young's modulus, defect dimensions, absorption coefficients, and so on. An example is shown in Fig. 2, while a summary of more important results is shown in Fig. 3. The noise level in the bogie area correctly remained unchanged for all modifications.

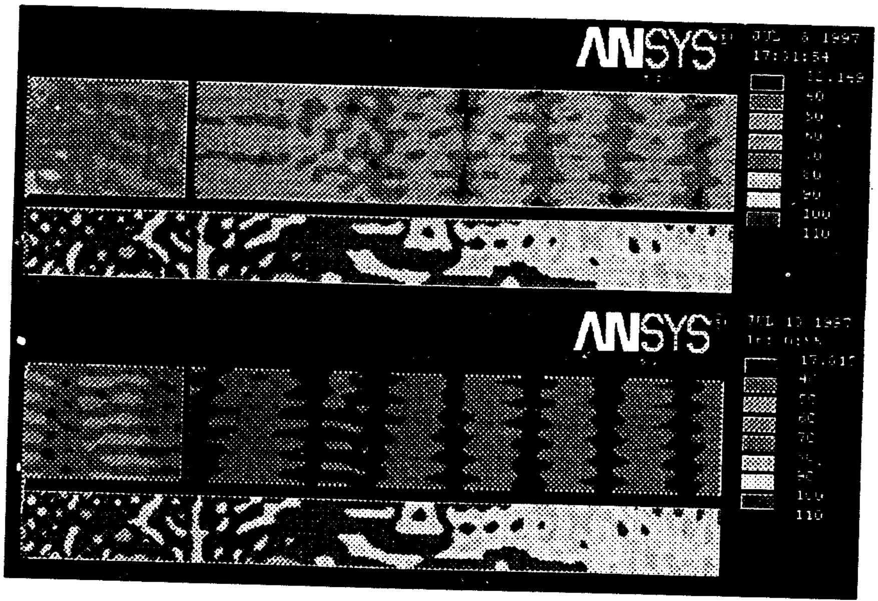

Fig. 2. Examples of FEM calculations results. Above: BASE model; below: model with defect in the vestibule floor eliminated.

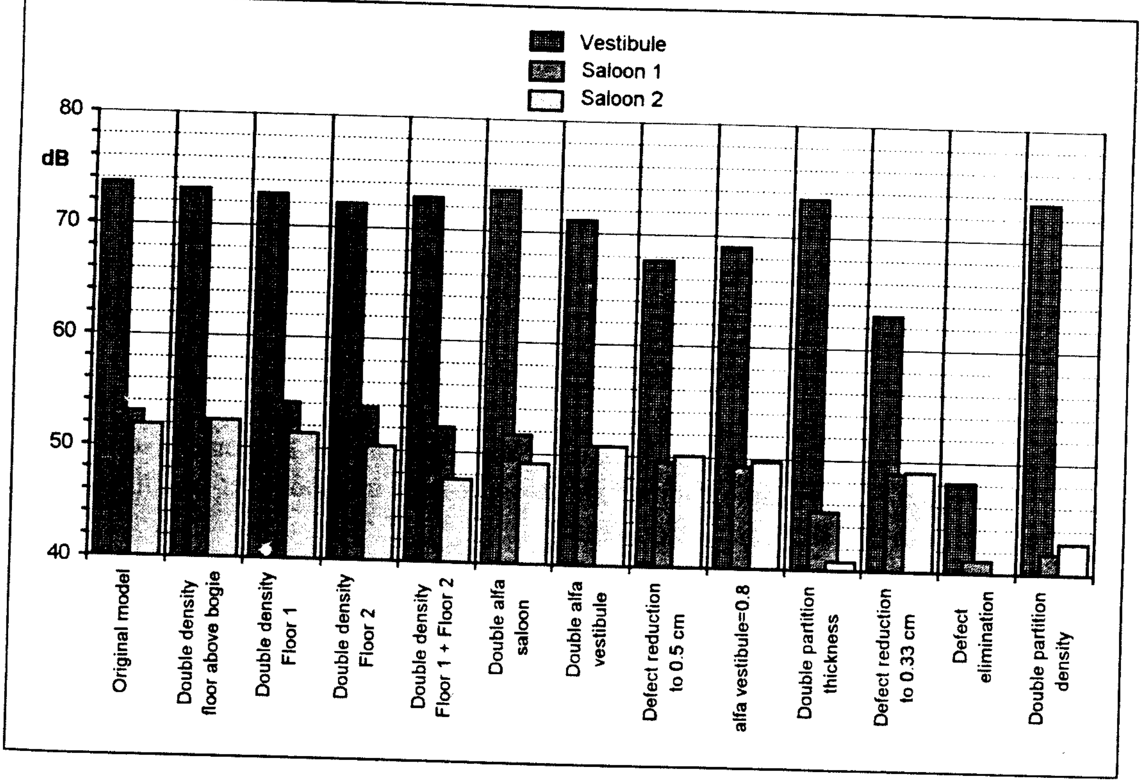

Fig. 3. Modification results compared to the original model simulation (1st columns).

The analysis of the results obtained with these simulations led to the following conclusions:

1. only some simulations show slight deviations from expected results even for very high variation of the parameters, confirming the good robustness of the model;
2. the noise mainly enters the coach from the vestibule, as all subsequent simulation prove;
3. the greatest improvement is obtained by acting on the gangway defect reduction, even if some values (for example by completely eliminating the defect) appear unrealistic, probably as noise due to surfaces vibrations is not considered here;
4. the partition has a strong influence on noise measured in both Saloon 1 and Saloon 2 positions, and this is a component to be redesigned in the future, even if the doubling of its density leads to unrealistic results probably due to the too rough description of the vestibule area;
5. the increase of the absorption coefficient of the vestibule reduces the noise in both the vestibule and the saloon;
6. the increase of the floor density does not appear to be a valid criterion to reduce noise except if the density is at least doubled on the whole coach;
7. the increase of the absorption coefficient of the saloon leads to little noise reduction.

CONCLUSIONS

In this work the results of a research on internal acoustics of a 2nd class coach of the ETRY500 are shown. A FEM model was built and validated through noise measured during specifically planned test runs. The use of the model allowed the identification of some possible acoustical enhancements and it proved to be a valid instrument for the designer of new or retrofitted passenger coaches.

ACKNOWLEDGEMENTS

The authors wish to thanks Prof. Renzo Ciuffi and Prof. Paolo Rissone of the Dipartimento di Meccanica e Tecnologie Industriali for their help in model set up and the continuous criticism in the results discussion phase.

BIBLIOGRAPHY

Bracciali, A., Ciuffi., L. and Ciuffi, R. (1994), "Metodo innovativo per la misura della rumorosità esterna dei convogli ferroviari", Ingegneria Ferroviaria 6, pp. 317-332.

Bracciali, A., Ciuffi., L. and Ciuffi, R. (1997), "Calibration of an On-Board Noise Measuring Device by Simultaneous Measurement of Trackside Noise of Three Different Wheelsets for the ETR500 F.S. Train", to be published on F1 (August 1997) Proc. Inst. Mech. Eng., Part F, Journal of Rail and Rapid Transit.

Bracciali, A., Ciuffi., L., Ciuffi, R. and Rissone, P. (1994a), "Continuous External Train Noise

Measurements Through an On-Board Device", Proc. Inst. Mech. Eng., Part F, Journal of Rail and Rapid Transit 208, pp. 23-21.

Brebbia, C. A. (editor) (1995), "Computational Acoustics and its Environmental Applications", Computational Mechanical Publications, Southampton.

Corbizi Fattori, A. (1996), "Analisi sperimentale, simulazione numerica e possibili miglioramenti dell'acustica interna dell'ETR500", Degree Thesis, Academic Year 1994-95, University of Florence, Italy.

Swanson Analysis System Inc. (1995), "ANSYS Acoustic and Fluid-Structure Interaction Manuals".