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INTERIOR NOISE STRUCTUREBORNE PATH PREDICTION IN A HIGH SPEED TRAIN USING "FE/SEA" HYBRID MODELLING METHODOLOGIES

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ABSTRACT

Acoustic comfort in the interior of the trains is a key parameter in the design of modern trains. Moreover, European legislation of interoperability sets limits of interior noise in driver's cab. New hybrid methodologies including coupling between FEM/BEM/SEA make it possible to carry out useful predictions in an industrial environment. ALSTOM is applying these techniques in the development of modern trains to achieve human friendly products for passengers and train personnel.

This paper presents investigation work related to the understanding of how structureborne energy travels through a high speed train structure and radiate noise in the driver's cab. To understand the physics involved, the « Hybrid FE/SEA » methodology was used. This method allows for a deep understanding of the propagation of energy from the bogie/equipments attachment points to the ear of the driver.

Included in this paper there is a preliminary work performed on a high speed train showing the main structureborne paths to focus on. FEM (Finite Element Method) vibration simulation is correlated with experimental data and the results are presented and compared with vibro-acoustics simulation results using « Hybrid FE/SEA ». Finally, the preliminary results show that the simulation models are predictive since it follows a fixed preset model building process and provide a good level of accuracy against test data

1 INTRODUCTION

High speed trains are today a reality connecting cities, hubs and regions. The use of railway transport instead of other means (aviation, automotive,…) is clearly a more environmental friendly solution. However, the increase of speed of these systems could carry other secondary effects affecting to the environment and to the comfort of users and train personnel. European union has regulated with the Directive 96/48/EC-2008/32/EC [1] (as known as Technical Specifications of Interoperability) the noise emission levels and interior noise levels for the driver's cab of conventional and high speed trains. This directive is affecting all the new train designs and refurbishment projects and therefore is leading the industry to achieve the noise targets to homologate its products. Alstom Transport, is designing its products to be compliant with TSI and to obtain competitive targets in aspects where TSI is not applicable (like passengers comfort).

Alstom Transport high speed products have been evolving from previous TGV (Orange TGV) up to last development AGV (*Automotive Grand Vitesse*). The work in this paper is focused in the previous development of AGV, Duplex TGV.

Duplex TGV is an articulated train with a driving locomotive as can be seen in the following layout:

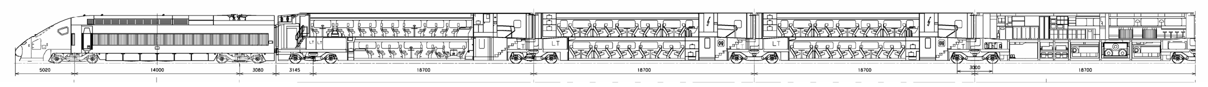

Figure 1: Duplex TGV layout

Before focusing in whatever type of prediction methodology and frequency range of interest, it is necessary to know experimentally what are the main contributions paths (airborne, structureborne) and the frequency content of each one of the main paths.

2 EXPERIMENTAL TESTS IN DUPLEX TGV DRIVER'S CAB

Alstom Transport has developed a technique based in Global Transfer – Direct Transfer methodology (GTDT), internally called META-X (in collaboration with ICR company). META-X is a technique based in transfer path analysis following the "signal" methodology and not the "force" methodology [2-3]. This technique has been applied by several automotive manufacturers during the 90´s [4-5] and has been updated during last years. The main objective of the technique is to quantify the main vibroacoustic transfer paths in a rolling stock.

The main advantage of META-X technique is its applicability to a rolling stock projects, where normally there is no prototype available:

- No need to estimate forces or measure forces
- Testing time reduced
- Frequency range of use
- Panel contribution and structureborne path could be measured at the same time
- Adapted to railway industry

META-X technique has been applied in the driver's cab of TGV Duplex to breakdown the main contribution panels and to rank the importance the different structureborne paths.

2.1 Description of the tests

The front bogie and the driver's cab were instrumented to quantify structureborne noise and panel contribution to driver's head position.

Structureborne noise. Attachment points of the bogie, traction motor and gearbox to the bodyshell were instrumented with accelerometers in order to control the vibration coming from these points and going through the structure to the interior of the cab. The main attachments measured were the following (see Figure 2): a) antiyaw dampers (left/right), b) vertical dampers (left/right), c) transversal damper, d) traction motor link, e) gearbox links.

Panel contribution. All the main panels around the target microphone inside the cab were instrumented with accelerometers and control microphones.

Antiyaw damper link | Vertical damper link | Gear box link

Figure 2:Example of structureborne paths measured

The methodology of GTDT needs two different type of experimental data coming from 2 type of tests:

- Static tests: *FRF* (Frequency Response Functions) and *Autopower spectra* with the train completely stopped and all the equipment off with hammer excitation that carachterize the dynamic inherent behaviour of the system
- Dynamic tests: vibration and noise measurements with the train running along the track at different speeds that corresponds to the behaviour of the system in operating conditions

Once both tests are completed, noise contributions from each path are computed.

2.2 Tests results

In Figure 3 it can be observed overall noise levels measured inside the driver's cab at the height of the driver's ear (L_{Aeq}). Measurements were done at 300 km/h with traction effort to keep a constant speed and without tractioning effort. An influence of the traction effort can be seen at the 1/3 octave of 2000 Hz due to gearbox contribution mainly.

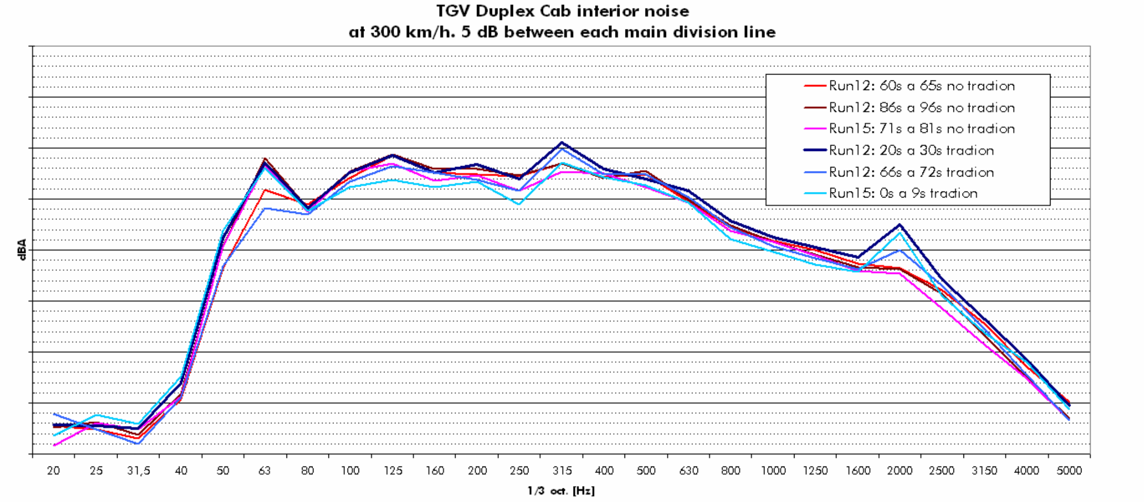

Figure 3: SPL measurements in driver's right ear position with traction effort and without it

In Figure 4, it can be observed the range of frequencies where the main paths are contributing showing a meaningful contribution to overall noise at low and medium frequencies.

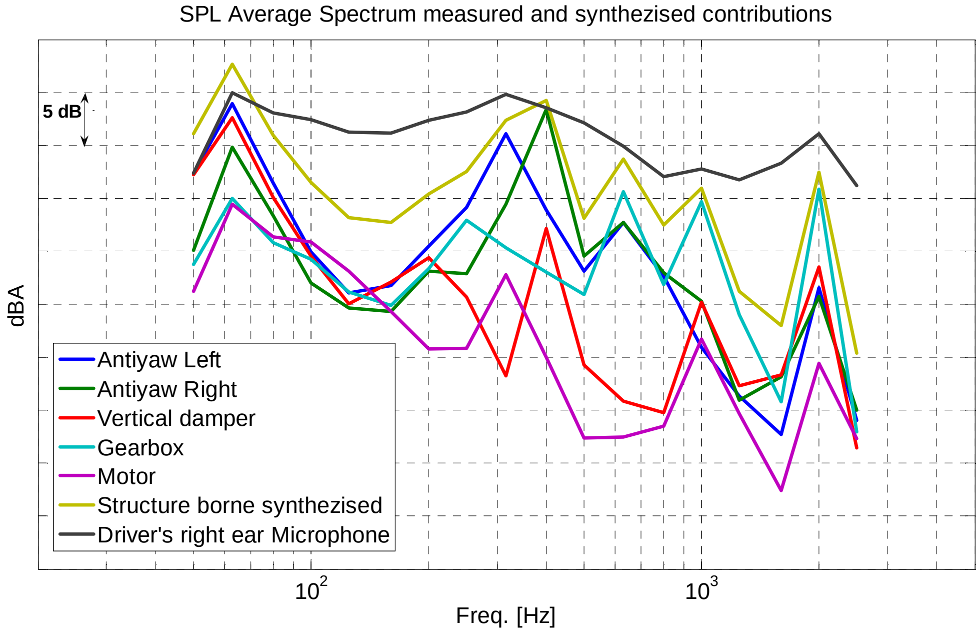

Figure 4 : Structureborne noise paths contributions

Analyzing the values measured in overall level the conclusions are that structureborne noise is close to be 50% of the overall noise level inside the cab, as can be seen in Table 1

Test condition	Measured - Structureborne synthesized
Driver’s cab in rear position, without traction	-3.2 dB
Driver’s cab in front position, with traction	-2.2 dB
Driver’s cab in front position, with traction	-3.6 dB

Table 1: Difference between SPL level measured and structureborne contribution synthesized

Grouping all the different contributions give the results in Figure 5, where it can be seen that the main contributor is the antiyaw damper link.

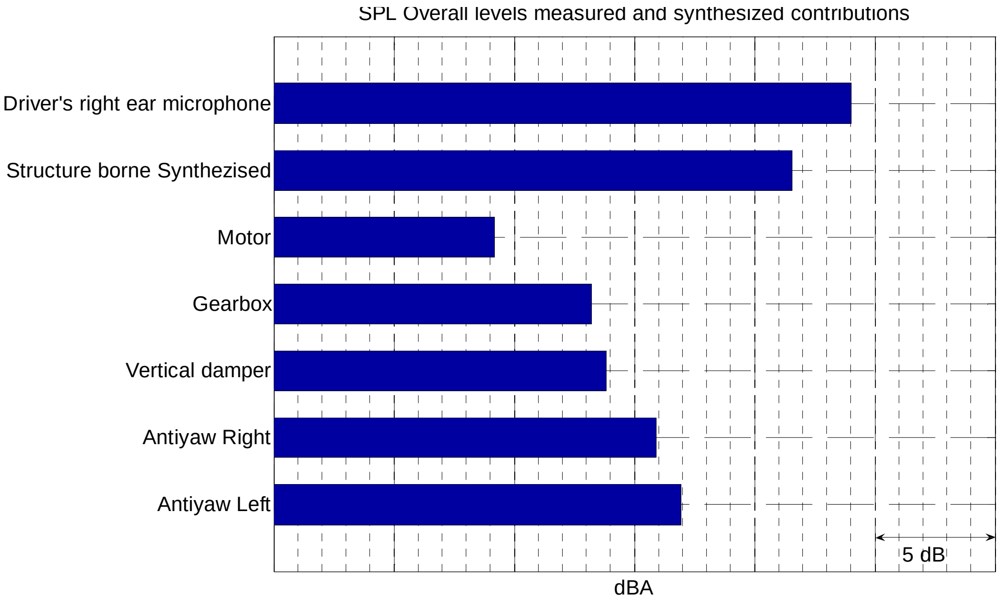

Figure 5: Structureborne paths contributions in overall levels

As a conclusion from the measurements and analysis, structureborne in the driver’s cab is not negligible at all and it covers a wide frequency range. It is influence can be up to 50% of the overall noise level. This is the main reason why it is needed to apply whole frequency range prediction techniques in future developments to achieve noise targets at very high speeds. Furthermore, aeroacoustic excitation of the driver’s cab is transmitted mainly through structureborne path (panels excited by turbulent flow, vibrating and radiating noise into the cabin).

3 INTRODUCTION TO HYBRID FE/SEA (FROM [6])

3.1 Hybrid FE/SEA method

A hybrid FE-SEA method ideally combines the low frequency performance of the FE method with the high frequency performance of SEA to produce a robust method that can be applied across the whole frequency range. However, the coupling of FE and SEA into a single model is difficult because the methods differ in two ways: (i) FE is based on dynamic equilibrium while SEA is based on the conservation of energy flow, and (ii) FE is a deterministic method while SEA is inherently statistical. Recently Shorter and Langley [8] have developed a new method of realising this coupling, which is based on wave concepts rather than the modal type of approach employed in reference [7]. At the heart of the method is a reciprocity result [9] regarding the forces exerted at the boundaries of an SEA subsystem. The method is briefly explained in the following paragraphs, It can be noted that references [8] and [9] contain a more formal and rigorous derivation of the hybrid method than that reported here.

In the mid-frequency range some components of a complex structure (for example thin panels) display short wavelength vibrations and are sensitive to the effects of random uncertainties, while others (for example beams) show little variation in their dynamic properties and are essentially deterministic. In the hybrid method proposed by Shorter and Langley [8], the deterministic components are modelled by using the finite element method, while the random components are modelled as SEA subsystems.

A key feature of the method is the concept of a “direct field” or “power absorbing” dynamic stiffness matrix associated with each SEA subsystem. Consider for example a thin plate that is excited at the boundaries. The excitation generates waves that propagate through the plate and are reflected repeatedly at the boundaries; the total dynamic stiffness matrix of the plate, phrased in terms of the edge degrees of freedom, has contributions from all of these reflections. Suppose now that the response is viewed in two parts: 1) The contribution from the initial generated waves, prior to any boundary reflections. This can be called the “direct field”. 2) The contribution from waves produced on the first and all subsequent reflections. This can be called the “reverberant field”. The direct field dynamic stiffness matrix can be defined as that resulting from the presence of the direct field waves – this matrix corresponds to “power absorbing” behaviour, in the sense that the direct field waves all propagate energy away from the boundaries. Such a matrix can be found analytically for each of the subsystems by a variety of methods.

3.2 The Hybrid FE/SEA equations

The starting point for the hybrid method is to identify those parts of the system response that will be described by SEA subsystems. The remaining part of the system (which can be considered to be the “deterministic” part) is then modelled by using the FE method. For example, it might be decided that the bending motions of the panels of a structure have a short wavelength of deformation and will be described using SEA subsystems. The bending degrees of freedom of these panels will then be omitted form the FE model of the system, at all points other than the panel boundaries. The relevant “direct field” dynamic stiffness matrix is then added to the FE model at the panel boundaries, and this augmented FE model is then used in the subsequent analysis. If the degrees of freedom of the deterministic part are labelled q, then the governing equations of motion (for harmonic vibration of frequency ω say) will have the form

$$D_{tot} q = f + \sum_k f_{rev}^{(k)}, \qquad D_{tot} = D_d + \sum_k D_{dir}^{(k)} \tag{1,2}$$

The summation is over the number of SEA subsystems in the model, D_{dir}^{k} and D_d represent the direct field dynamic stiffness matrix associated with subsystem *k*. Furthermore, *Dd* is the dynamic stiffness matrix given by the finite element model of the deterministic part of the system, *f* is the set of external forces applied to this part of the system, and represents the force arising from the reverberant field in subsystem *k*, which is not accounted for in D_{dir}^{k}. The matrix D_{tot} is the dynamic stiffness matrix of the FE model (excluding the SEA subsystem degrees of freedom), when augmented by the direct field dynamic stiffness matrix of each SEA subsystem. It should be noted that equations (1) and (2) are exact – all that has been done is to split the forces arising from the SEA subsystems into a direct field part, which is accounted for by D_{dir}^{k}, and a reverberant part which is carried to the right hand side of equation (1). The following result (Shorter and Langley [9]) is central to the development of the hybrid method:

$$S_{ff}^{(k),rev} \equiv E\left[f_{rev}^{(k)} f_{rev}^{(k)*T} \right] = \left(\frac{4E_k}{\omega \pi n_k} \right) \mathrm{Im}\left\{ D_{dir}^{(k)} \right\} \tag{3}$$

Here E_k and n_k are respectively the (ensemble average) vibrational energy and the modal density of the *kth* subsystem. Equation (3) implies that the cross-spectral matrix of the force exerted by the reverberant field is proportional to the resistive part of the direct field dynamic stiffness matrix, which is a form of diffuse field reciprocity statement.

These basic equations can be combined and rewritten to lead to the following energy balance equation for subsystem j:

$$\omega\left(\eta_j + \eta_{d,j}\right)E_j + \sum_k \omega\eta_{jk} n_j \left(E_j / n_j - E_k / n_k\right) = P_{in,j}^{ext} \tag{4}$$

And the cross-spectral matrix of the response q can be written as follows:

$$S_{qq} = D_{tot}^{-1}\left[S_{ff} + \sum_k \left(\frac{4E_k}{\omega\pi n_k}\right)\mathrm{Im}\left\{D_{dir}^{(k)}\right\}\right]D_{tot}^{-1*T} \tag{5}$$

Equations (4) and (5) form the two main equations of the “Hybrid FE/SEA” method. It is clear that these equations couple FE and SEA methodologies: equation (4) has precisely the form of SEA, but the coupling loss factors η_{jk} and loss factors $\eta_{d,j}$ are calculated by using the FE model augmented by the direct field dynamic stiffness matrices; furthermore, equation (5) has the form of a standard deterministic FE analysis, but additional forces arise from the reverberant energies in the subsystems. If no SEA subsystems are included then the method becomes purely FE; on the other hand, if only the junctions between the SEA subsystems are modelled by FE, then the method becomes purely SEA, with a novel method of computing the coupling loss factors.

4 SIMULATION. A PRELIMINARY STUDY

Building predictive models for structureborne noise has been simplified by the introduction of the “Hybrid FE/SEA” method. No need to build separate models and try to stretch low and high frequency methods beyond their limits and hope for the best. The “Hybrid FE/SEA” method uses the benefits of both FE and SEA method and provides the engineers with the means to couple these methods to bridge the mid-frequency gap that was traditionally unreachable.

The implementation of the “Hybrid FE/SEA” methodology in the commercial software VA One [10] enables engineers to build a model that includes both FE and SEA subsystems and to automatically couple the subsystems together. The result is a single model in a single environment that can be solve locally or on a cluster.

Different strategies can be adopted when building “Hybrid FE/SEA” models. One can decide to model the structure using FE and model the fluids using SEA making the model building process quite simple and fast. In fact, the structural FE model can be used as is. Only SEA cavities have to be created and connected to the structure. A more refined approach looks at the structure itself and finds appropriate candidates regions to be modelled as SEA. Once identified, the SEA subsystems and FE subsystems are created and connected. Then sources are defined and the model is ready to be solved.

4.1 The structure studied

In this study, the focus is placed on the front part of the locomotive called the cabin. The rear part of the assembly is referred to as the body. The cabin structure is composed of beamlike components, small and large panels. This type of structure is ideal for Hybrid FE/SEA methodology since the beamlike components can be modelled as FE and the panels as SEA. Some components such as the floor panel, the windscreen and the side glasses are built from layers of different materials bonded together. The front part of the cabin is designed for crash & safety purposes and finally the cabin is covered by a polyester nose.

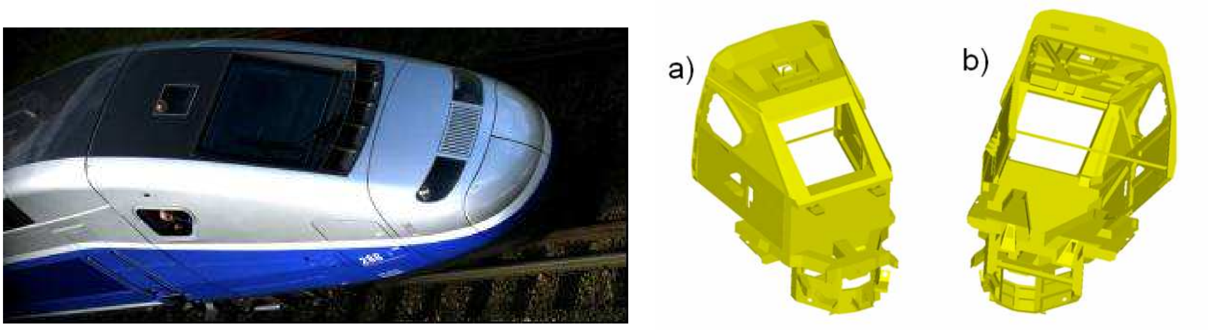

Figure 6: TGV Duplex Locomotive Cabin – a) External view, b) Interior view

4.2 Model building process

In the case of the locomotive cabin simulation, the structure is divided into SEA and FE regions. The process to decide whether a region should be modelled as FE or SEA is mainly based on mode count. The frequency of interest is 100 to 1000 Hz. One of the benefits of the “Hybrid FE/SEA” method is the reduction of the number of FE degrees of freedom (DOF) since these are replaced with a SEA description of a region. It allows the FE mesh to be refined and attain higher frequency with the same initial number of degrees of freedom. It is common knowledge that an SEA subsystem should contain a minimum number of modes at the lowest frequency of interest to be valid. In this preliminary study, a criteria of 3 to 5 modes per 1/3 Oct. band was used. The following figure shows a preliminary partitioning based on this criterion.

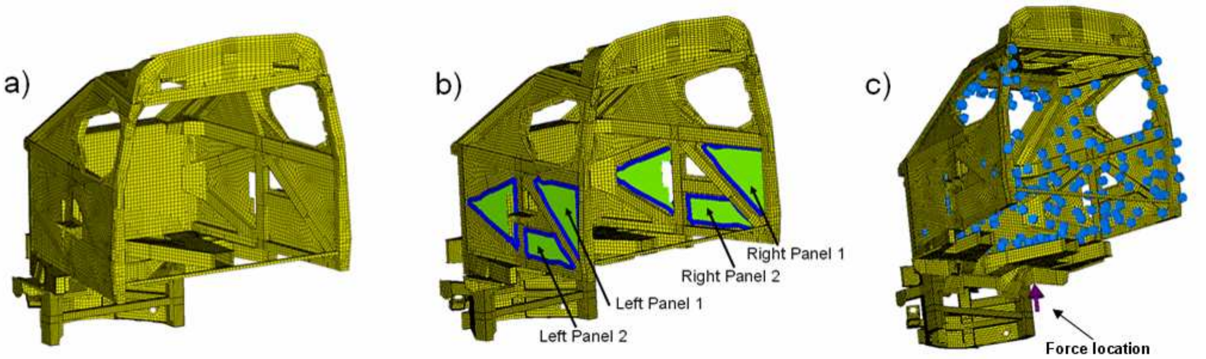

Figure 7: *a)* Full FE model *b)* "Hybrid FE/SEA" model *c)* Location of force (violet arrow) and virtual accelerometers (Blue dots).

Once the FE and SEA subsystems are created, an automatic algorithm connects all subsystems where node connectivity is found. Following the partitioning of the model, different sources can be defined. For this preliminary study, a unit force is applied at a stiff frame location under the cabin (See Figure 7). Virtual accelerometers are created on the FE content to enable the computation of average response on the full FE content and comparison with SEA mean acceleration predictions. The only measured data used in this model are the damping loss factors (DLF) of the assembled BIW cabin. At this point, comparison between full FE and "Hybrid FE/SEA" results is possible. Figure 8 shows comparison between acceleration levels for 2 panels on the right side of the cabin modelled as FE vs hybrid FE/SEA.

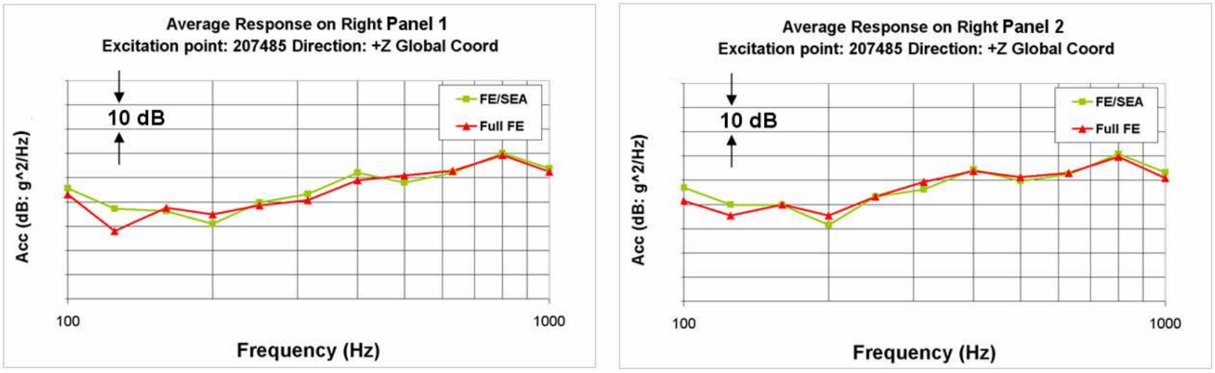

Figure 8: Comparison between full FE and "Hybrid FE/SEA" prediction on two panels of the right side of the cabin (Left= panel 1, Right= panel 2).

4.3 Experimental testing

A measurement campaign was performed to ensure proper simulation process is adopted. A single cabin was followed on the production line to ensure measured data was providing insight on a particular structure and did not include any variability from one cab to the other. The tests performed included a modal analysis of the cab in a free-free condition (see Figure 9). Also over 100 FRFs were measured for a series of different configurations assessing the effect on the cabin vibration response from *i)* residual stress after welding *ii)* damping paint *iii)* attachment of cabin to body *iv)* attachment of polyester node *v)* attachment of windshield *vi)* addition of trim, cockpit, seat … Furthermore, elemental tests are performed on some complex components such as the laminate windshield and multilayer floor. Finally, the fully trimmed configuration is tested for vibration and acoustic response.

Figure 9: Experimental modal analysis setup of the driver's cab BIW

Since the "Hybrid FE/SEA" model relies on the FE and SEA description, it is imperative that the FE model be well correlated with test data. Accuracy of the results will depend on this correlation when comparing test data with simulation. This correlation is under way and therefore results presented here should be considered as preliminary.

4.4 Preliminary results

As stated earlier, the aim of this study is to be able to model properly the structureborne noise paths from the different sources in the bogie and links of the traction equipment to the sound pressure levels in the cabin. Once this modelling is mastered in the frequency range of interest, design changes can be applied to the model and design decisions can be taken and verified afterwards. The preliminary comparisons between test data, FE and FE/SEA simulations are mainly focussed at this point on the structural transfer function between the source points in the area of the bogie and the vibration of the panels and beams of the structure. Figure 10 shows comparisons between measured and predicted FRF from a force underneath the cabin (see Figure 3) to panel 1 and 2 on the left side of the cabin.

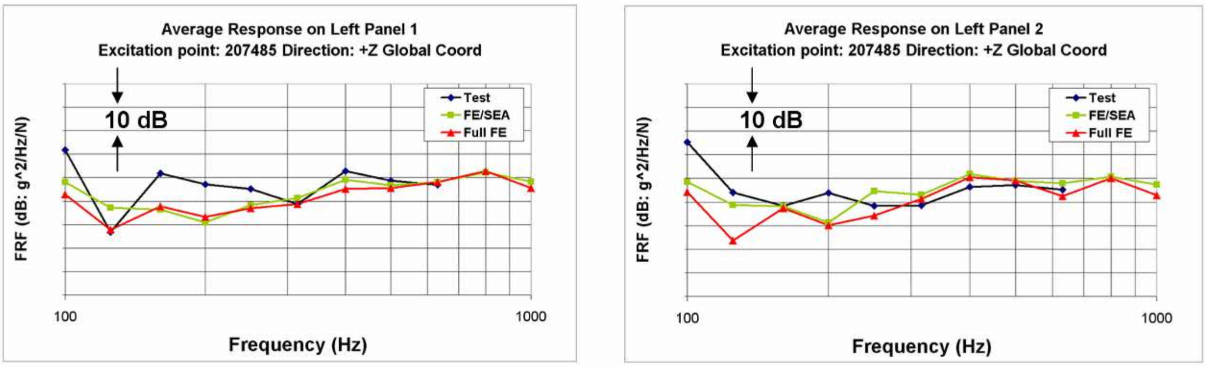

Figure 10: Comparison between average acceleration response due to an unitary input force for panels *Left Panel 1* and *Left Panel 2*

Considering that the FE model is still being correlated with test, preliminary results show a reasonable level of accuracy for transfer function between the source points and panel vibrations. When test data become available for the acoustic radiation path further comparisons will be possible.

5 FUTURE WORK

A deeper investigation on the modes in band criterion will be performed to see how far down the frequency range can the SEA subsystems be pushed. Modelling of the floor panel, windshield, side glasses, polyester nose, cockpit and trim will also be investigated. Finally, the acoustic path will be included in the model to allow prediction of SPL at the driver's head.

6 CONCLUSIONS

An hybrid FE/SEA prediction methodology has been applied to a real industry case. The results obtained are quite promising showing a good correlation between FE prediction and FE/SEA hybrid methods, allowing in the future to work with hybrid models to represent the vibroacoustic behaviour of high speed trains in the whole frequency range. The use of FE/SEA hybrid models covering the medium-high frequency range allows to handle the type of problem described and it will be specially useful for large models (like the whole driver's cabin or passengers area) where classical FE models are not possible to work with.

The results obtained show a good accuracy for the vibration prediction at frequencies higher than 200 Hz, nevertheless further efforts are needed to increase the accuracy at lower frequencies by having a better FE/Experimental modal basis correlation.

The software tools for the hybrid FE/SEA used during this application have showed a good integration into the industrial process. The technology is being integrated into the Alstom design process to assure reliable structureborne noise predictions during early stages of the design of a new product.

7 ACKNOWLEDGEMENTS

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REFERENCES

[1] Directive 96/48/EC – Interoperability of the Trans-European high speed rail system – Technical specification of interoperability – “Rolling stock” subsytem

[2] F.X.Magrans, Journal of Sound and Vibration, ‘Method of measuring transfer paths’, 74(3), 321-330, (1981).

[3] O.Guasch, Journal of Sound and Vibration, ‘Direct transfer functions and path blocking in a discrete mechanical system’ , doi:10.1016/j.jsv.2008.10.006, article in press (2008)

[4] U.Fingberg and T.Ahlersmeyer, 3rd Automotive Acoustics Conference, ‘Noise path analysis. A new approach based on practical experience’, (1992)

[5] H.R. Tschudi, Unikeller Conference 91, ‘The force transmission path method: an interesting alternative concerning demounting tests’, (1991)

[6] R.S. Langley, P.J. Shorter and V. Cotoni, Novem 2005, ‘A hybrid FE-SEA method for the analysis of complex vibroacoustic systems’, (2005).

[7] R.S. Langley and P. Bremner, Journal of the Acoustical Society of America, ‘A hybrid method for the vibration analysis of complex structural-acoustic systems’, 105, 1657-1671, (1999).

[8] P.J. Shorter and R.S. Langley, Journal of Sound and Vibration, ‘Vibro-acoustic analysis of complex systems’, (2004).

[9] P.J. Shorter and R.S. Langley, Journal of the Acoustical Society of America, ‘On the reciprocity relationship between direct field radiation and diffuse reverberant loading’, 117, 85-95, (2005).

[10] VA One® , Users Guide, Theory and QA. The ESI Group 2008