Edinburgh, Scotland
EURONOISE 2009
October 26-28

Total vehicle SEA modelling in the real world

Joe Venor
ESI Group

Marc Burghardt
Michael Eberle
Audi AG

ABSTRACT

In automotive terms Statistical Energy Analysis has traditionally been used solely for the prediction of high frequency airborne noise, with only occasional forays into structural and aero-acoustic excitations, more commonly assessed in aerospace or maritime structures.

Over the past decade, Audi AG and ESI, in conjunction with consultant partners has pushed the use of SEA within vehicle projects for both “virtual” vehicles at the start of a project and later prototype automobiles searching for the total vehicle solution, including structure-borne, airborne and aero-acoustic noise and vibration sources for frequencies above 250Hz. In the following Paper, results are provided down to 100Hz, but shaded to indicate the reducing confidence at lower frequency.

The current paper outlines the total vehicle modelling in VAOne and validation of a total vehicle model based entirely on supplied CAE data and correlated against tests made under wind tunnel and real-world test-track conditions. The paper also outlines the use of the model for noise path tracking and interior Sound Pressure Level improvement.

1. INTRODUCTION

Over the last decade, the use of Statistical Energy Analysis within the Automobile industry has begun to be accepted as a useful method for assessing and controlling airborne noise. SEA has often been used in conjunction with test to assess the behaviour of existing structures, but has also been shown to be an excellent tool for the prediction of the effects of adding absorption, isolation and mass to specified vehicle noise paths. In general, therefore, SEA has most commonly been used for the modelling specific sections of the vehicle (such as a firewall or door) in order to examine the Transmission Loss through particular panel and sound package combinations.

This, however, has not been using SEA to its full potential, there are often several paths for noise into a vehicle, both airborne and structure-borne, which has been shown to be significant at lower frequencies (<1kHz) [1]. To consider only a single Transmission Loss path is therefore to ignore potentially more serious routes. It has therefore been the belief of both ESI Group and Audi AG that in order to sensibly consider the overall noise levels within a car it is necessary to model the whole vehicle, to consider both structural and airborne sources, to consider external flanking paths and aero-acoustic effects, and to do this as early in a vehicle project as possible, in order that there be enough time to effect changes in the vehicle development.

A series of projects have therefore been conducted, firstly to model an existing car, then to model a virtual vehicle[2] in order to assess the ability of SEA to predict behaviour before prototypes are available, then to add the capability to predict external sound fields [3,4] and wind noise behaviour [5].

Furthermore, whilst SEA has also been traditionally used to assess A-B comparison changes, the prediction of overall levels (potentially even before prototype phase) would be immensely useful as it can therefore be used to predict the relative importance difference noise sources and paths, to this end projects were carried out to test real vehicles and use measured excitations to drive the SEA model and thereby assess the significant noise paths under real-world conditions. This paper outlines the methods and results obtained from this undertaking.

2. MODEL PREPARATION AND EXCITATION

A. Modelling

Modelling with Audi has always attempted to model as many of the possible noise paths as can be modelled under the constraints of SEA. The model comprised in the order of approximately 800 panels, 100 beams and 200 cavities.

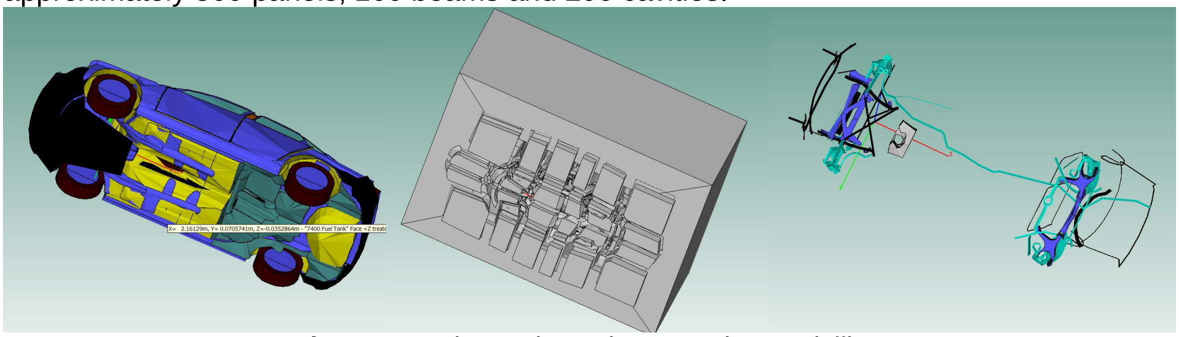


Figure 1: Body, Cavity and Suspension Modelling.

The body was modelled predominantly with flat or singly curved shells in order that cavities may be associated with the rail, pillar and sill structures in order to allow the assessment of baffles in order to block the flow of noise.

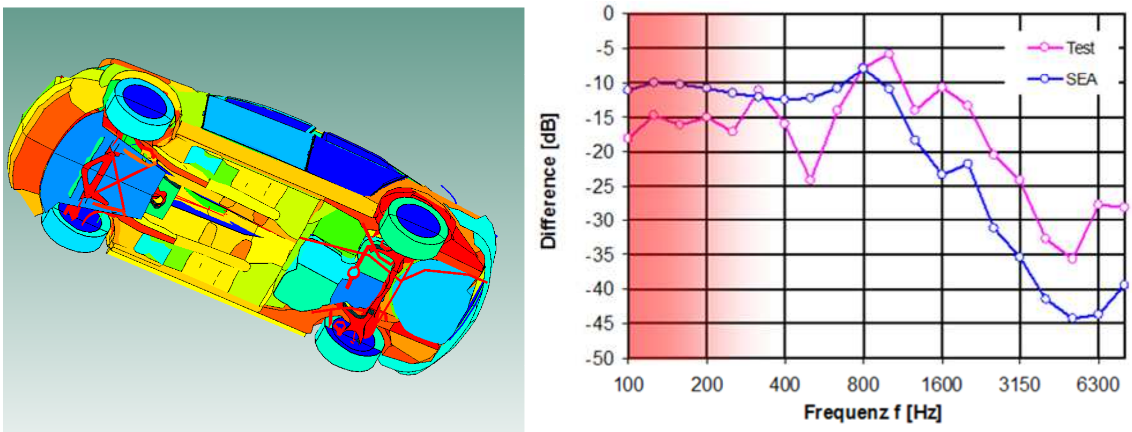


Figure 2: Structural Energy Thermogram and plot of measured and predicted energy transfer from a wheel hub via the suspension to the vehicle body

One of the assumptions of SEA is that of weakly coupled subsystems, in the case of automobile modelling it is useful to be able to separate the SPLs at different internal locations or at different locations around the vehicle in order to account for the sound field generated by diffraction [4], in other words to separate single cavities into many smaller cavities, which being part of a whole are by their definition not weakly coupled. To this end the internal cavity was separated into 13 cavities, the external cavities into a 3 layer system as outlined in previous papers and boundary conditions set accordingly to account for a stronger coupling than SEA would normally predict.

The suspension of the vehicle was also modelled, predominantly using beams, which were used to transfer structural power, but not acoustically active as given their low mode counts this would have been problematic in SEA terms. These were connected to each other and to the vehicle body using isolating springs to simulate the behaviour of the mounting and bushes. Figure 2 shows the flow of energy within the suspension and chassis of the vehicle, and indicates the level of agreement between test and SEA prediction for the transfer of energy from the wheel hub to the vehicle body.

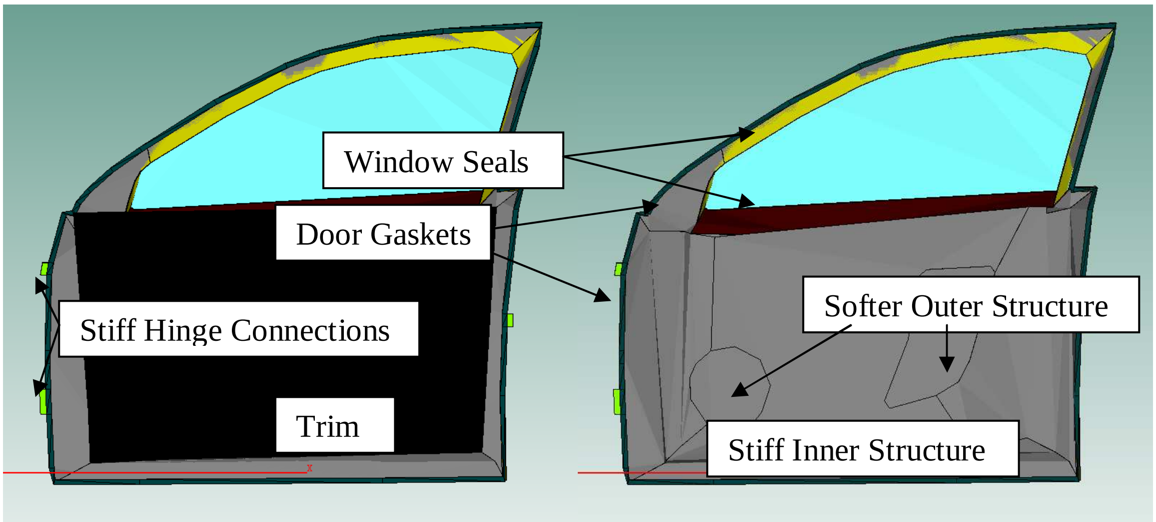


Figure 3a: Example of Complex Structure Modelling – gaskets and seals serve both acoustic and structural purposes

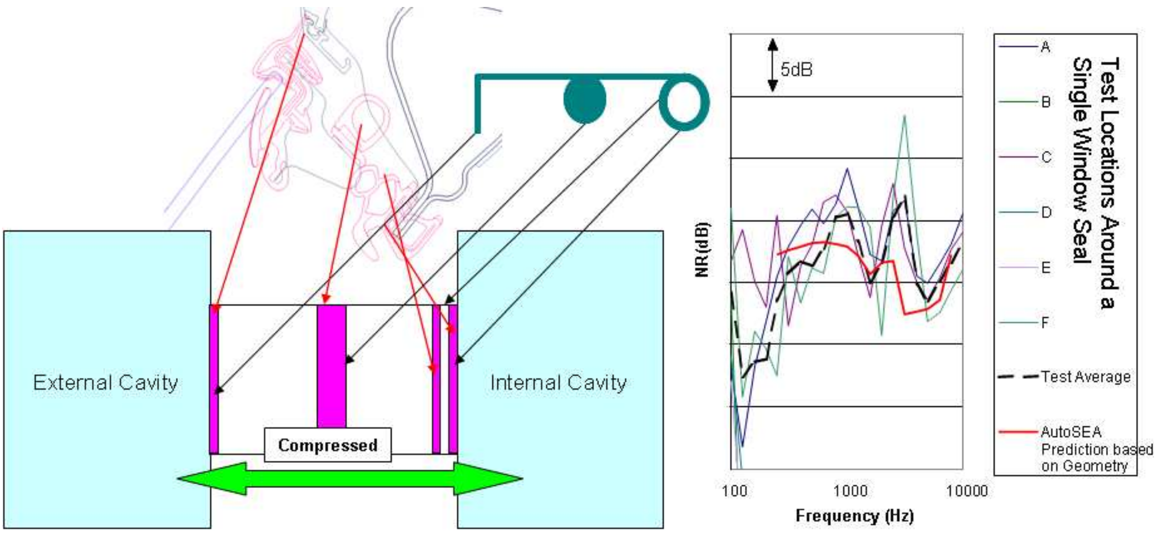


Figure 3b: Modelling of Seal and Gaskets

Figure 3a illustrates the level of detail modelled for a stiff structure, combining a stiff inner frame with more acoustically active large panels such as the door outer panel and the window, with stiff non-radiating connecting components. In addition leaks into the door, via the water holes and around the waist seals were also included, together with explicit modelling of the gasket and window seals taking into account the number of layers, materials and treatments employed as shown in Figure 3b.

B. Test

An extensive series of tests were conducted to characterise the vehicle under a large number of conditions:

- Constant Speed – 5 different Speeds in 2 gears on rough and smooth roads
- Constant Speed – 5 different Speeds in 2 gears on a dynamometer
- Revving in neutral at rpm equivalent to those used in the constant speed tests
- 3rd Gear Wide Open Throttle 1000-5000rpm in 1000rpm bands
- 2nd Gear Partial Throttle 1000-5000rpm in 1000rpm bands
- Wind Tunnel Turbulent Layer at 100 and 140kph

Measurements of Sound Pressure levels in the engine bay, exhaust and tyre patches were made, together with accelerometer measures of vibration levels on the wheel hubs, exhaust mounting locations, engine block and gearbox.

C. Excitation

Excitations to the model were the defined as a set of more than 20 excitations in order to account for all structural and airborne sources measured. In the case of airborne sources, these were defined as Power inputs in the following manner.

- 1W Power input was applied to each of the source cavities (tyre patch, exhaust outlet, engine bay) simultaneously, and an SPL determined for each cavity.
- For each cavity in turn a new Power was determined using
  Power = 1W*(Desired SPL for given location/SPL resulting from 1W input)

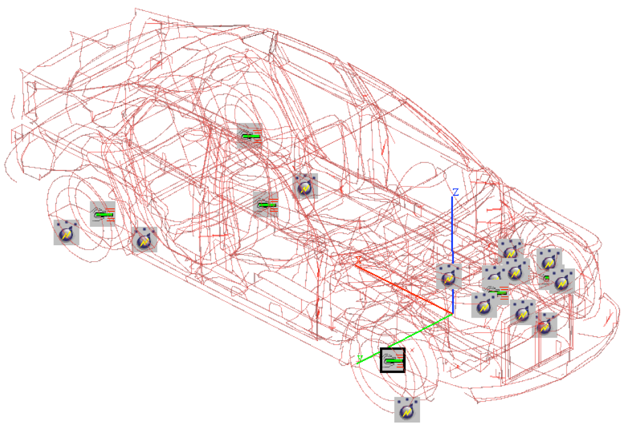


Figure 4: Excitation Locations.

A similar method was initially used for defining the structure-borne inputs, but the model was well enough conditioned that almost identical results were obtained with energy constraints, so for ease and speed of application, velocity constraints upon panel and beam subsystems were used to define the structural excitation locations.

Finally for aero-acoustic noise, TBL excitations were used based on a revised cavity arrangement akin to that proposed by De Jong et al [6], these were originally intended for aerospace applications above 0.6mach, but have been found, under suitable conditioning to give very useful results for automotive applications.
`

3. RESULTS

A. Sound Level Prediction

Figure 5 indicates the measured and predicted interior SPLs for a vehicle driven at constant speed in 5th gear. Agreement with the results from the test track was excellent, except at high frequency (> 4kHz), where the model significantly underpredicted the SPL. The usual explanation for this would be that at high frequency, aerodynamic noise would become the dominant source. The vehicle under consideration however was known to be extremely aerodynamically efficient, which combined with presence of this effect at speeds as low as 50kph, where aerodynamic noise is not usually a concern indicated that another cause was behind this difference.

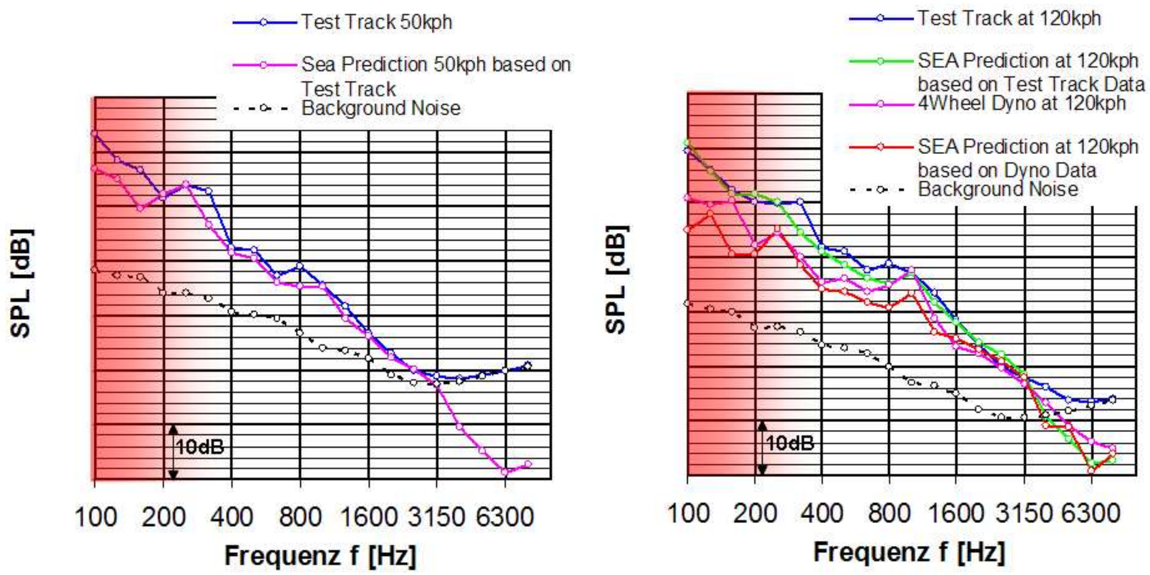
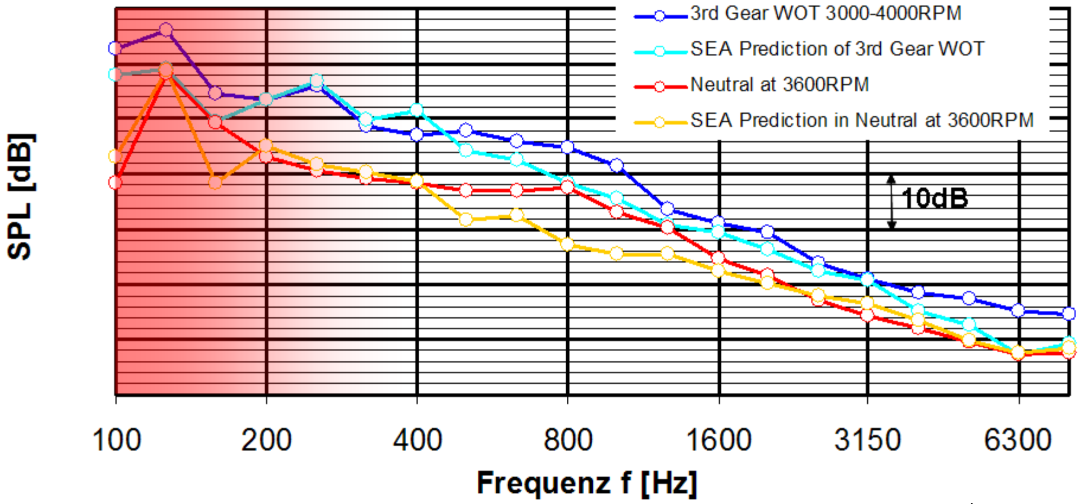


Figure 5: Comparison of Measured and Predicted interior SPL levels on the Test Track and Dyno.

Figure 5 shows the background noise level at the test track, which is completely consistent with the levelling off of the interior SPL at both speeds. In this case therefore the SEA prediction was likely to be far closer to the actual generated noise within the vehicle than that measured on the test track. Tests conducted on the Dynamometer, with a lower background noise level proved this point, with agreement between test and prediction extending all the way up to 8kHz.

Figure 5 illustrates the validity for predictions under constant speed, but under different driving conditions, different noise sources become dominant, Figure 6 illustrates the agreement obtained when powertrain noise sources became more significant, agreement was also close but an under-prediction was observed at 800Hz, the fact that this underprediction is not observed under other excitation cases would indicate that it is strongly linked to the powertrain – most likely associated with a firewall pass-through, the characterisation of which is still at least partly dependent upon test data.



`**Figure 6**: Comparison of the Measured and Predicted interior SPL levels under 3rd Gear Wide Open Throttle and under coasting.

B. Aerodynamic Noise

As stated in the previous section, there is a known valid reason for underprediction at high frequencies and high speeds, and that is the occurrence of aero-acoustic noise sources. In the current work, studies were undertaken in the wind tunnel in order to characterise the turbulent flow around the vehicle at different speed.

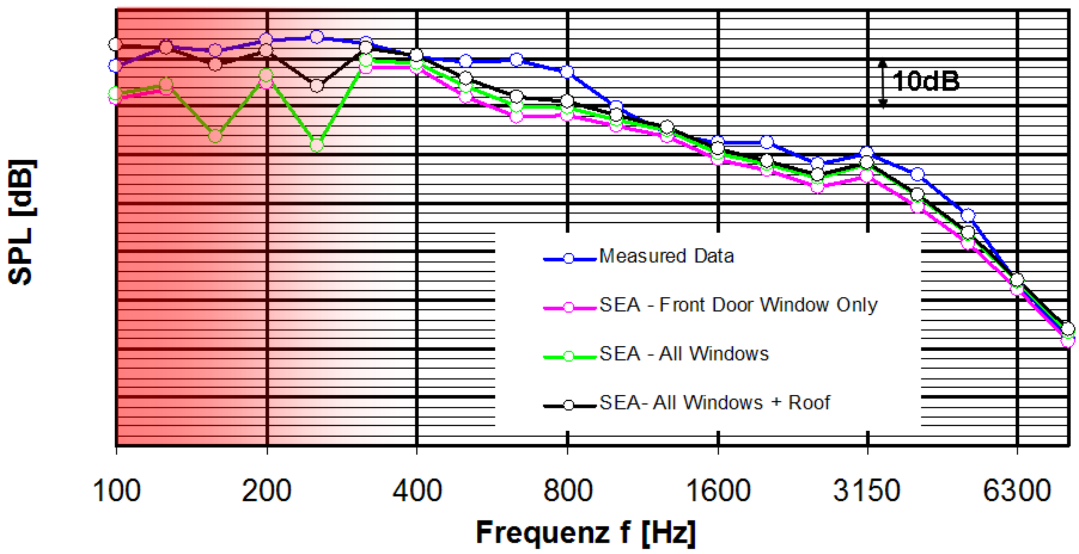


Figure 7: Comparison of the Measured and Predicted Interior SPL levels with different aerodynamic noise sources for a wind speed of 140kph.

Figure 7 shows the internal SPL at the driver's head location for the vehicle in the Wind Tunnel. Measurements were made on a production car with taped door gaps and a foam block underneath the front apron to reduce the influence of gap and underbody noise. The magenta line shows the SPL predicted based excitations applied at the front door windows only. Two features are clear, firstly that they did not account for the whole interior SPL (in that other sources also contribute, such as on the windshield and roof) and secondly that there were drop-outs at low frequency. This was likely due to the formulation of TBL which is intended for fully resonant systems than in this vehicle model, hence the small windows yielded drop-outs whilst the larger windshield and the steel components did not.

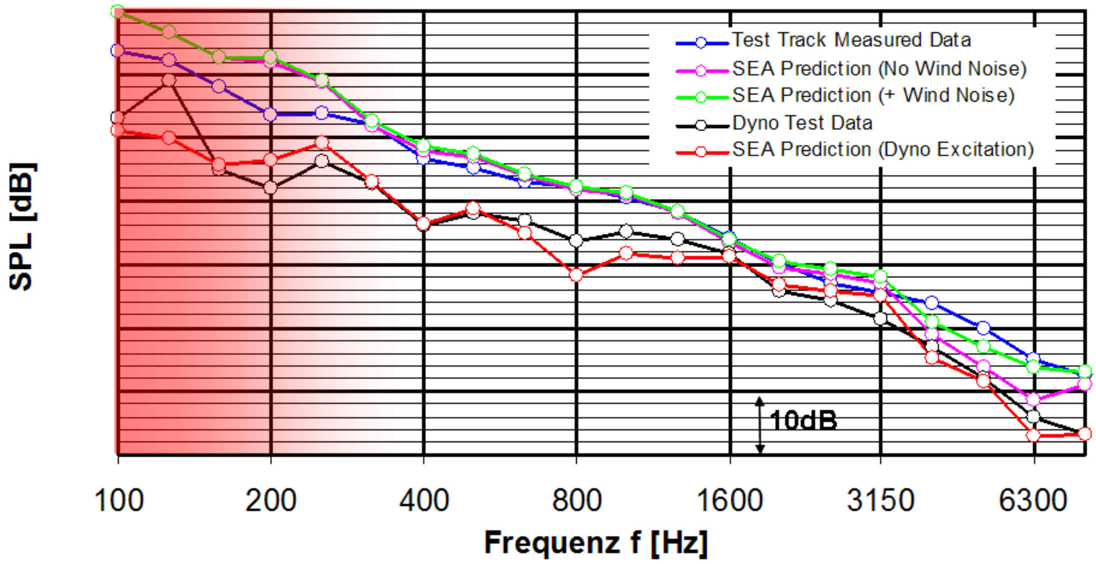


Figure 8: Comparison of Predictions with Measured Data for Dyno and Test Track with and without Wind Noise Excitation

Once all the window excitations were added, the red line resulted, which showed much closer agreement with the measured data, and when the roof excitation was added, agreement between test and predicted interior SPL was exceptionally promising. It should be taken into account that it is still not possible to implement local narrow band noise sources such as overeflown gaps or low frequency noise sources due to limitations of the SEA method. Figure 8 shows how the addition of the wind noise excitations accounted for the gap between predicted and measured internal SPL at high frequency under the high speed applications as expected.

C. The Significance of Structure-borne Noise

The majority of SEA models in the past have been concerned with airborne excitations only, commonly comprising models of perhaps 200-300 subsystems, with no structural connections and with exterior sound fields applied by the use of constraints. Previous studies [1] have indicated that at lower frequencies (below about 800Hz) the structural inputs of the suspension and the powertrain can dominate.

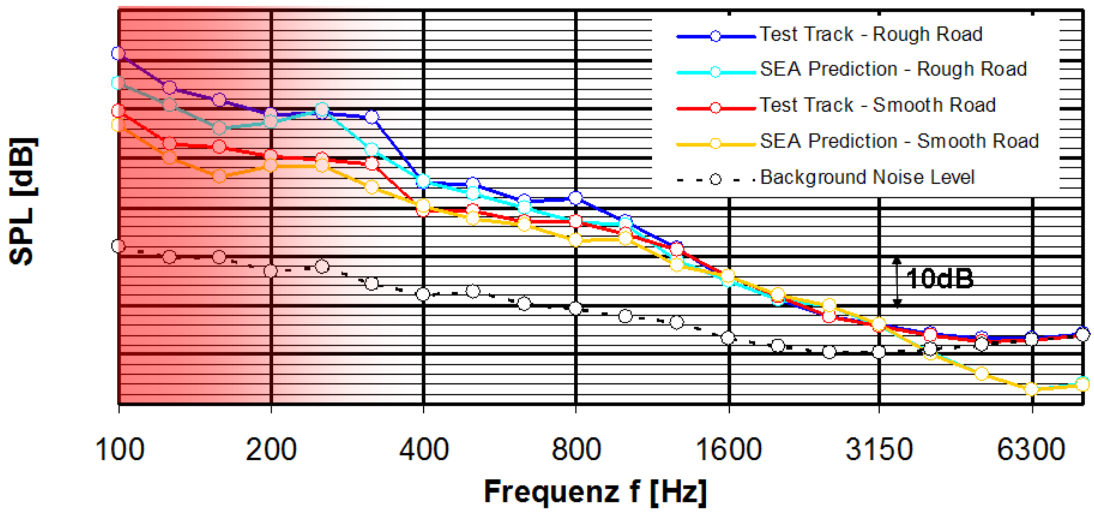


Figure 9: Comparison of Overall Sound Level Predicted for Smooth and Rough Roads indicating the dominance of Structure-borne Sources at Lower SEA Frequencies.

Figure 9 illustrates this point admirably, showing the interior SPL resulting from driving the same car at the same speed on two surfaces, one rough and one smooth, yielding an increase of as much as 10dB for the rough surface, attributable to structure-borne inputs as the tyre patch noise difference was very small. In the current work a considerable amount of effort was put into modelling the correct power flow through both the vehicle body and the suspension itself and as Figure 9 shows, the model was capable of predicting the effect on internal noise of the increased structural inputs.

D. Idealised and Real World

SEA has long been used to predict the effect of changes to a system, by means of AB comparisons. In the case of a fully virtual vehicle, this is almost unavoidable as true excitation data is unavailable. Therefore in order to study the behaviour of the vehicle, one would use a series of idealized excitations or excitations based on a nominally similar predecessor vehicle.

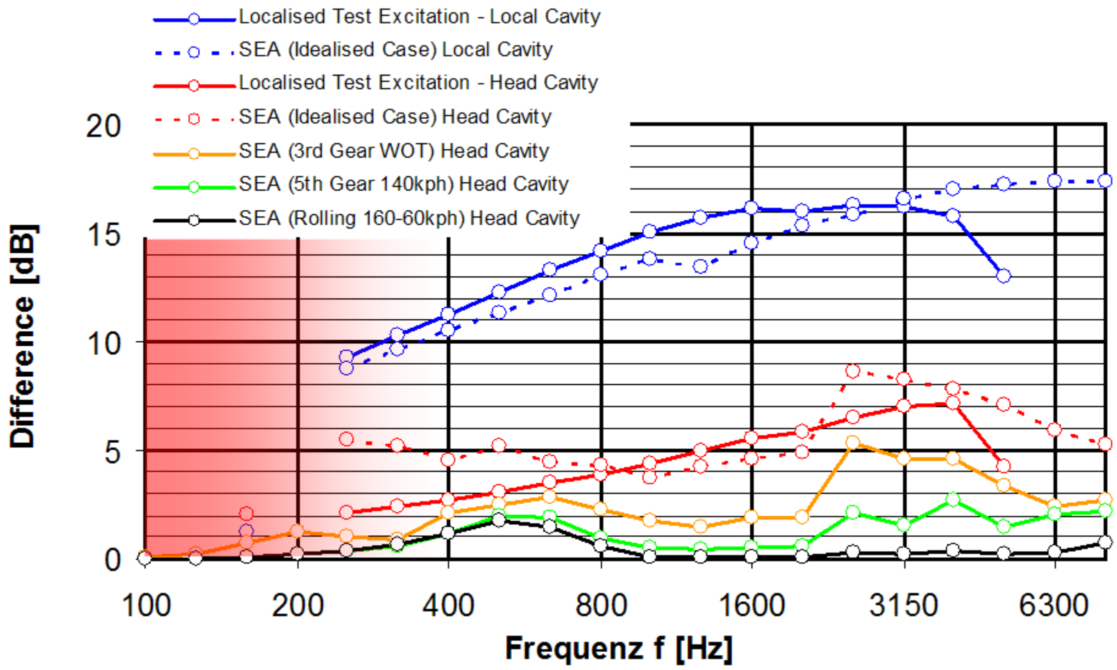


Figure 10: Comparison of the Effect of a Seal Modification on Internal Noise under Idealised and Real-World Excitation Cases.

Idealised excitations usually take the form of a 1W power input into the subsystems known to contain the excitation points of the real vehicle. Figure 10, shows just such a study performed for a significant seal connected with engine noise. A 1W power input to the adjoining cavity was made and the effect of modifications to the seal observed local to the seal and at the driver's head were predicted and measured based on a highly localised sound source. Figure 10 indicates the very strong effect of this seal on internal noise.
In the real-world, however, there are many flanking paths and other sources which can mask the effect of this seal. Figure 10 shows the effect of the same modification under real-world excitation conditions. In the case of coasting (very little powertrain input) the effect is reduced to less than 1dB over almost the entire frequency range, whilst for the Wide Open Throttle condition, differences almost as high as the idealised case were predicted.

E. Optimisation

The test vehicle in the current work was already an extremely quiet vehicle so initial studies to improve the interior SPL proved fruitless without incurring significant mass penalties, focus therefore turned to the reduction of mass for no detrimental effect on interior noise.

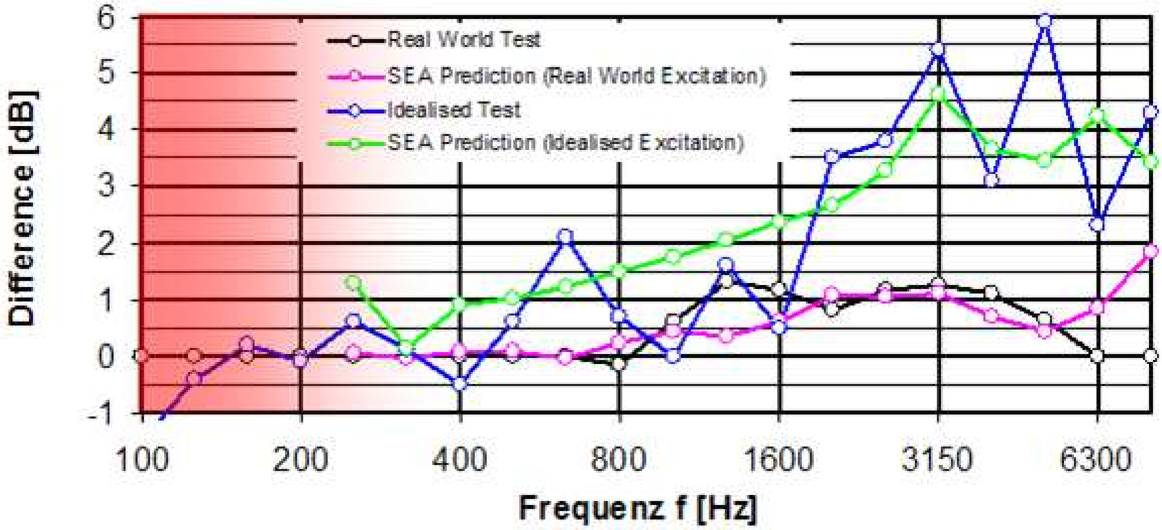


Figure 11: Effect of removal of absorption pad.

Figures 11 and 12 show the results of two of the mass reduction studies carried out by Audi and test partners. They concern the removal of a large absorber and a large damping pad respectively. Figure 11 indicates the effect of removal of the absorber on SPL in the vehicle interior for an idealised excitation close to the absorber (increasing internal noise by as much as 5-6dB) but also shows that under real-world loading, the effect is likely to be masked down to about 1.2dB. The over prediction of the effect around 1kHz was likely the result of the previously described under prediction in powertrain noise transfer in the 800-1200Hz region.

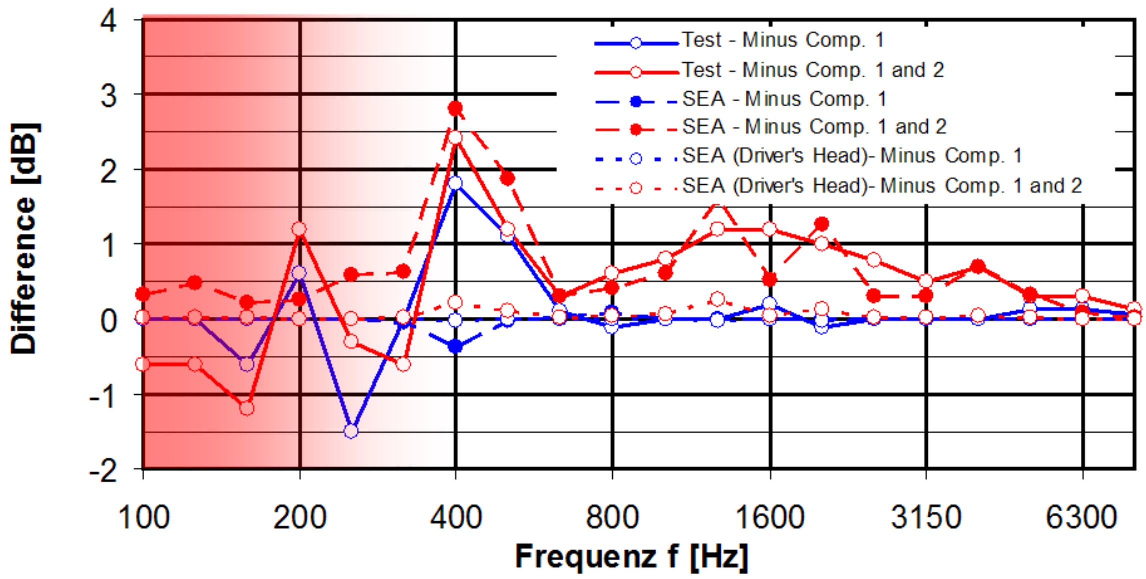


Figure 12: Effect of removal of large damping and mass pad.

Figure 12 shows the effect of the removal of a two component system accounting for several kg, from the vehicle body, under real-world steady speed excitation. Immediately adjacent to the body location, both test and SEA modelling predict an increase of something above 1dB, whilst at the head locations the effect was predicted to be less than 0.2dB. Tests to confirm this fell below the repeatability of the measure.

The extremely sharp response at 400Hz was present in the prediction but at a significantly reduced level. Test shows this to have resulted from a highly tonal response which cannot be predicted by averaging procedures such as SEA, and indicate the kind of study for which a hybrid approach might be considered to be more appropriate.

5. CONCLUSIONS

The conclusions of this paper build on the conclusions of previous work within ESI and Audi AG.

- SEA is capable of predicting both the airborne behaviour and the structure-borne behaviour in automobiles above approximately 250Hz
- The external sound field can be predicted using SEA and simple diffraction relationships
- Internal Sound Pressure from aerodynamic noise can be predicted based on Wind Tunnel test measurements – CFD is the next step.
- The relative importance of different noise paths can be evaluated under real-world conditions and resources therefore applied where they will provide most benefit
- SEA can be used to optimise trim performance and mass, by removal or reduction of least beneficial trim package components.
- Additional work is required on the characterisation of firewall seals and grommets – which are still currently dependent upon test for realistic characterisation.

REFERENCES

1. J. Venor, O. Leost and T. Bharj "Using SEA as a part of the vehicle design and development process", Proc. Of 1st AutoSEA Users' Conference, San Diego, 2000

2. J. Venor, A. Mueller and S. Nintzel "Sea Modelling and validation of structure and airborne interior noise in existing and virtual automobiles", Proc. Of EuroPAM Conference, Mainz 2003

3. J. Venor and M. Burghardt, "SEA modelling and validation of sound-fields and seals in automobiles", Proc. EuroPAM Conference, Potsdam 2005

4. J. Venor and A. Zopp, "Using SEA to model near field external sound pressure distributions based on automobile geometry", Proc. Of Vibro- Acoustic Users' Conference, Koln 2007.

5. M. Eberle, R. Schilling, M. Brennberger and G. Wickern "Statistische Energieanalyse der Windgeräusche am Kraftfahrzeug", DAGA 2008.

6. R. de Jong, T. Bharj and J. Lee "Vehicle Wind Noise Analysis Using a SEA Model with Measured Source Levels", SAE-Paper 2001-01-1629