Experimental modeling techniques for understanding road noise*

Dave Fish, Simon Roberts and Maria Franco-Jorge – MIRA

Low frequency road noise phenomena in passenger vehicles have generic characteristics associated with tyre, suspension and body dynamics for a wide range of vehicle styles and classes. Experience has shown that transmission path concepts are inappropriate due to low modal densities and that understanding road noise requires a modal approach. The current techniques for experimental modal acquisition are limited by non-linearities of the suspension and tyre dynamics. Likewise the analysis processes are limited containing 'noise' as a result of statistical variance, high levels of modal damping, and a complex force generation mechanism.

In the fields of modal analysis and operational measurements MIRA has developed a number of experimental techniques to overcome some of the current limitations and provide a better understanding of the interaction between suspension and tyre dynamics within the typical operating environment. With a good understanding of both the natural and forced modes of the suspension system it will be possible to optimise the design of future suspension systems for NVH.

MIRA has been involved in the measurement and development of suspension systems for road noise for many years. Road and tyre noise is increasingly a subjectively dominant part of the in-vehicle noise for a wide range of vehicles, particularly at low and mid- speeds. Analysis of the in-vehicle noise field for road induced noise has shown that the 63 and 125

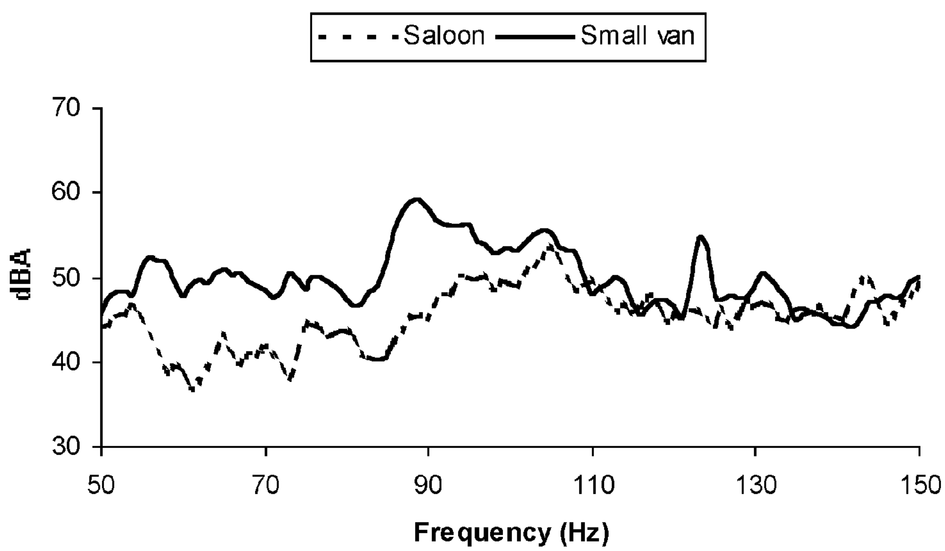

Figure 1. Typical in-vehicle narrow band noise responses for two different vehicle types

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Hz octave bands are both significant contributors to the total acoustic energy and correlate strongly with the subjective perception of low frequency tyre noise. Experience has shown that, not surprisingly, most of the energy in this frequency range is structure-borne. To better understand the structural paths MIRA has employed many of the techniques traditionally available to NVH development engineers such as Transfer Path Analysis (TPA), Principal Component Analysis (PCA), and virtual running mode analysis. These techniques have been specifically developed to address the analysis of multiple incoherent sources. Whilst these have proven invaluable in identifying major paths and have helped to differentiate between front and rear suspension contributions they are limited in their ability in accurately quantify and determine the detailed dynamics and interactions between the body, suspension, and tyre. The development of solutions for road noise require there to be little or no compromise with handling and ride characteristics, therefore solutions for suspension system design and future concepts will need the application of accurate models of the entire vehicle 'corner' characteristics.

Low frequency tyre noise subjectively dominates the majority of typical saloon vehicles currently in production at low and mid-speeds (up to 100 km/h). Through experimentation this has been identified as being primarily correlated to energy in the 63 and 125 Hz octave bands. This noise, perceived as a boom, can be observed on various surfaces with both coarse and smooth profiles. Although it is variable in intensity between different vehicles, speeds, tyre types, and surfaces the sound quality characteristics are similar in most cases. Figure 1 shows the typical power spectral density (PSD) levels for two very different vehicle types in the frequency range of interest. Modal analysis shows that the broad band energy characteristics are the associated with a number of modes of the tyre, suspension, and body. This is discussed in more detail below.

Consequently, whilst it is necessary to consider the isolation provided by the suspension system across this broad frequency range, it is essential that the modal characteristics and interaction between the suspension sub-systems are understood if its design is to be defined for superior all round dynamic performance. Simply increasing the isolation of suspension bushes will significantly compromise the ride and handling characteristics. The need for accurate modal modeling is paramount.

Transfer path analysis

TPA is used to identify the importance of a particular subsystem body-attachment point towards interior noise in the vehicle. It allows the force transmitted to the body through the bush to be quantified and, when combined with the body sensitivity at that point, provides an estimate of the resulting partial pressure. Unfortunately, TPA is less effective when applied to road noise issues than for power unit applications.

For a TPA based on measured dynamic stiffness the differential acceleration across the mount is very small due to the high dynamic stiffness associated with suspension mounts and so the results are overly sensitive to the accuracy of these measurements. Similarly methods based around an inversion of the system inertance matrix are adversely effected by the relatively low modal density of the body combined with the high dimensionality of the problem. Further to this, the suspension represents a sub-system that is stiffly mounted to the bodyshell but is still operating in a frequency range where its behaviour is controlled by the stiffness and damping of its bushes. This implies that the relationship between bush stiffness and force transmission is non-linear while the TPA model is fundamentally linear. This can only be addressed with a modal model.

Ideally the method should identify any phase effects from the combination of paths, particularly when considering the orthogonal paths at a single bush. For this to be achieved a suitable signal needs to be available to which all measurements can be referenced. As the vehicle is forced by several uncorrelated inputs these are not readily accessible as reference signals and the system response has to be utilised. Normally, principal component analysis of at least four interior microphone recordings is conducted to generate virtual spectra for the road inputs. This means that as the system response changes these virtual spectra are changed, irrespective of changes to the local behaviour. Thus any changes effectively invalidate the original analysis and prevent a sequential approach to development being followed.

Modal considerations

MIRA's two-wheel-drive chassis dynamometer has 1.6 m diameter rollers and for this technique they are fitted with a number of impact strips to provide a repetitive input when in operation. The fundamental frequency of the excitation is directly proportional to the road speed. Analysis of the operating deflection shapes at the fundamental and higher orders of impact frequency highlight the suspensions underlying natural response whilst the suspension system is operating under realistic operating conditions. This technique is useful for defining the balance of energy transfer between the front and rear suspension systems to interior noise. Analysis of such data is straightforward due to its coherent discrete nature and the controlled operating environment and input characteristic. However, since these are operating measurements and the input force function is not defined it is not possible to use this information for detailed modal modelling of the suspension system and therefore it is only useful as a problem solving tool.

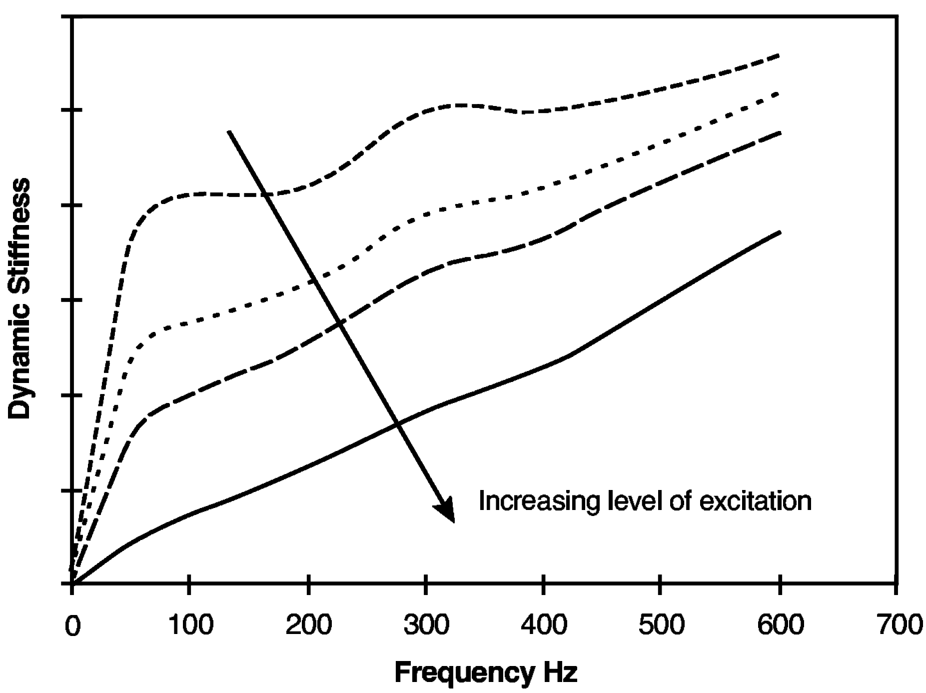

Figure 2. Effect of excitation level on dynamic stiffness of a shock absorber

The operating environment of suspension systems is extremely variable and complex and it is important that account is taken of the operating envelope when conducting a modal acquisition. There is a significant difference in the dynamic stiffness between a static and rolling tyre as a result of changes to the contact patch surface and tyre inertia. Consequently, MIRA has developed a modal measurement method using a vehicle chassis dynamometer to allow for wheel rotation and loading for a fully built vehicle. Using a multiple input excitation this method generates hub responses similar to those seen on the road. This has significantly improved the quality of modal analyses for complete suspension systems. Investigations have shown that shock absorber stiffness controls some of the mode characteristics of the suspension system. Dynamic stiffness measurements of the shock absorber component for various levels of quasi-static excitation highlighted the non-linearities of the component causing a reduction in its dynamic stiffness levels with increasing quasi-static loading (figure 2).

In the operating environment these are generally excited by low frequency primary ride dynamics, and high amplitude, low frequency impacts. By accounting for these quasi-static dynamics through low frequency oscillation of the vehicle chassis, observable changes to the suspension mode behaviour can be seen during laboratory testing.

These approaches account for operating parameters influencing non-linearities associated with tyre and suspension components, though the current methods used do not accurately replicate the road input profile. However, the general findings are that these methods correlate well with observed track based operating measurement profiles.

Separating tyre and suspension sub-systems for experimental measurement and modelling has a number of benefits. Firstly, it simplifies the experimental procedures for measuring the suspension system as there are no rotating components to consider. Secondly, the experimental modelling of the tyre (a generic component of every vehicle) can have benefits and applications to a very wide range of vehicle suspension models. Thirdly, an understanding of the coupling between the two sub-systems can be extremely beneficial for explaining poor road noise performance on particular vehicles and assist in de-tuning suspension components so reducing their sensitivity to road inputs.

Suspension modelling

Figure 3 shows the typical experimental approach that is used to measure the suspension natural frequency response. Note that the suspension is simply supported using an air bag and the hub is excited using a multiple input source. The centre of the hub is retained at the correct position for a normally loaded vehicle as with its road wheel fitted.

Figure 3. Multiple excitation of vehicle suspension with wheel and tyre removed

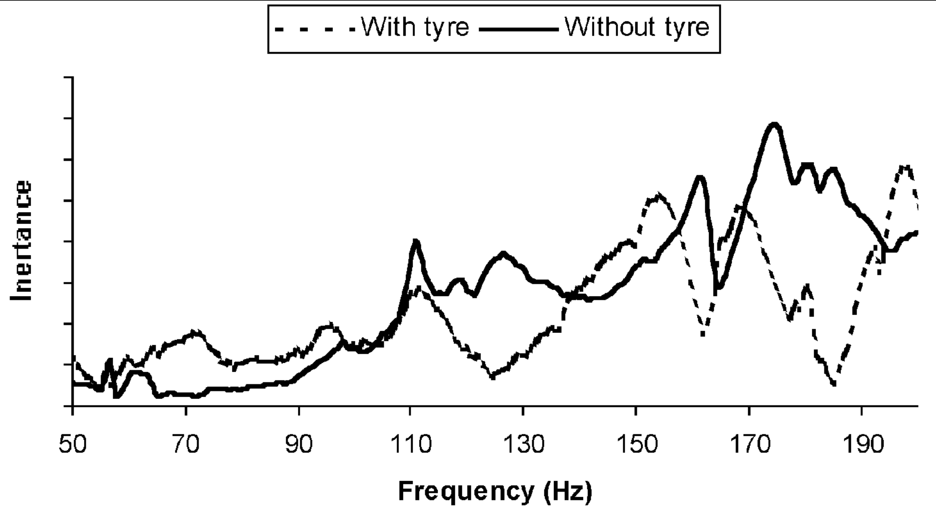

Figure 4. Influence of the tyre dynamics upon the frequency response function of the suspension system

Using this approach the typical frequency response function for a suspension system without the wheel and tyre subsystem can be seen to be significantly modified (figure 4). Damping effects due to the tyre can be seen, and the coupling of modes at other frequencies is evident.

Road wheel and tyre modelling

In order to generate a suitable modal model of the wheel and tyre sub assembly a combined empirical and analytical approach is adopted. A basic mass spring model is used with the relevant system parameters determined from a series of tests. System identification techniques are applied to extract suitable values which, when applied to the model, produce the correct modal response. In this way the operating conditions for the tyre can be accurately incorporated into a model as the wheel and tyre subsystem can be tested under operating conditions.

At MIRA the dynamic response of the tyre is determined using an instrumented hub which allows the system response to be determined under a number of conditions (figure 5). This hub enables the force to be measured for the 6 degrees of freedom present. The excitation is generated on the MIRA chassis dynamometer using various impact conditions where wheel speed, impact frequency, impact severity and pulse shape can be controlled. Figure 6 shows a typical response with both vertical and fore/aft forcing levels showing high levels around 60 to 100 Hz, typical of the 1st structural tyre mode frequencies. From these data, the tyre model parameters can be determined and a suitable modal model generated.

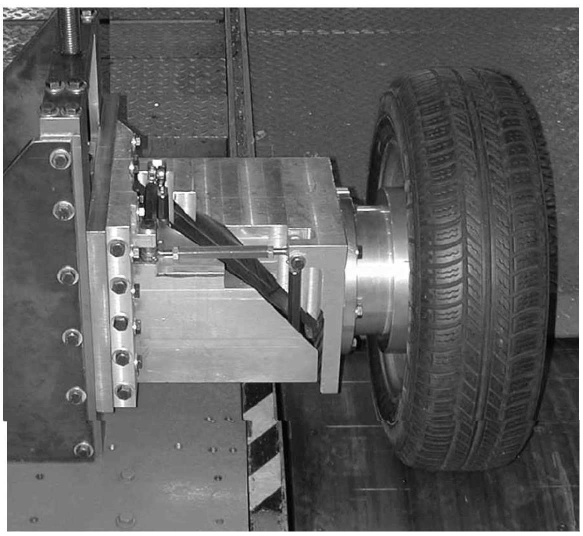

Figure 5. Instrumented hub for road wheel dynamic measurements.

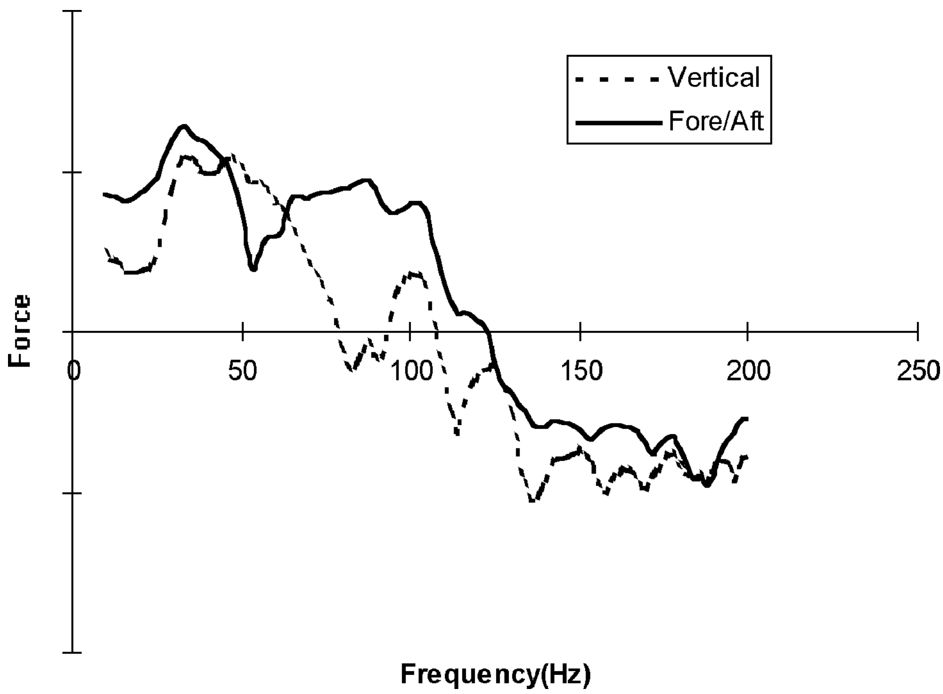

Figure 6. Typical force response functions for a repetitive impact on a chassis dynamometer

Conclusion

Experience has shown that road noise issues are primarily concerned with energy in the 63 and 125 Hz octave bands. As a result of low modal densities and high suspension bush stiffnesses TPA approaches are limited in their ability to model the suspension behaviour, and a modal approach is required. Due to the specific operating environment of the suspension system novel modal acquisition techniques have been developed to better understand the natural response of the vehicle suspension system. Separation of the tyre dynamics from the suspension has further helped to better understand the coupling of the modes. As a result experimental models are being developed to provide the necessary information for target setting, problem solving, and design concepts which accurately define the natural suspension behaviour and predict the in-vehicle acoustic response for suspensions systems in the normal operating environment.

Dave Fish studied at the Institute of Sound and Vibration Research at Southampton University completing a degree in Engineering Acoustics and Vibration in 1987. He worked in NVH at Jaguar before moving to MIRA in 1990 to take up a DTI-funded collaborative research project concerning vehicle occupant response to noise.

Simon Roberts studied at the University of Southampton where he received his BSc and obtained his MSc from the ISVR. He worked at Jaguar Cars for eight years before joining MIRA's NVH department in 1992. He has worked on three EU-sponsored research programmes as well as various vehicle-development projects.

Maria Franco-Jorge studied at the Escuela Tecnica Superior de Ingenieros Industriales de Madrid (Spain) and at the University of Newcastle (UK). In 1995 she completed a six-year engineering degree covering a number of disciplines. In the final three years she focused on mechanical and automotive engineering. Following six months' work experience at Automotive Products plc she joined MIRA in 1996 as a graduate engineer in the NVH department.