SAE TECHNICAL
PAPER SERIES

2010-36-0448
E

Transfer Path Analysis of Road Noise: Overview and customized approaches for road rumble noise

CÉSAR HELOU TEODORO DA SILVA
ALVARO COSTA NETO
LEOPOLDO PISANELLI RODRIGUES DE OLIVEIRA

SAE BRASIL
Sociedade de Engenheiros da Mobilidade

FILIADA À
SAE International

Congresso 2010 SAE BRASIL

XIX Congresso e Exposição Internacionais
de Tecnologia da Mobilidade
São Paulo, Brasil
05 a 07 de outubro de 2010

Este trabalho técnico/científico recebeu apoio financeiro do **Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq – Brasil**

CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico

AV. PAULISTA, 2073 - HORSA II - CJ. 1003 - CEP 01311-940 - SÃO PAULO – SP

2010-36-0448

Transfer Path Analysis of Road Noise: Overview and Customized Approaches for Road Rumble Noise

César Helou Teodoro da Silva
Ford Motor Company Brazil Ltda.

Alvaro Costa Neto and Leopoldo P. R. de Oliveira
São Carlos School of Engineering - University of São Paulo

ABSTRACT

The purpose of this paper is to experimentally analyze structural-borne contributions of noise, vibration and harshness during tire rolling, also called Road NVH, in a passenger vehicle using energy transfer path analysis method (TPA), applied in a case study. During the investigation, the influences of the accelerations and forces through the A-arm front suspension bushings are highlighted due their contribution to the estimated overall interior noise, which is correlated to measured overall interior noise. The structural contribution begins as a direct result of tire vibration from surface interactions. These mechanical vibrations, mainly below 450 Hz, are transmitted to all chassis and body subsystems, resulting into noise and vibration perceived by the passengers in the cabin interior. This study is motivated by improvements in Powertrain NVH and Wind Noise, which unbalance Road NVH on various conditions. Thus, when seeking the refinement of tactile, psycho-acoustic and dynamic comfort, motivated by the market that requires increasingly lighter vehicles, with less environmental impact, low cost and high quality, it is necessary to develop the concepts of the entire chassis, hard points and body to optimize dynamic performance ratio versus NVH sources balance.

INTRODUCTION

Transfer Path Analyses, also referred to in the literatures as Source Contribution Analysis and Noise Path Analysis, is one of the most important NVH methodologies from last decade that helps understanding the role of different sources and how do they spread through different paths [1]. In automotive development, several concepts have evolved to combine experimental techniques from in-laboratory and operational conditions, on-road tests, and even numerical models, to estimate structure and airborne energy contributions, which can be applied for both Powertrain and Road NVH cases [1, 2]. The basis of the TPA process is to quantify the total energy response in terms of individual transmission paths and sources contributions into the vehicle. This approach allows breaking down each of the partial load contributions (force and volume velocity) and frequency response functions (FRF) between the load locations and the considered targeted responses. As an example, the interior sound pressure at a particular position can be expressed as:

$$P(\omega) = \overset{\text{Sstructure-borne}}{\sum_{j}} \mathrm{F_j}(\omega) \cdot \left(P/F(\omega)\right)_j + \overset{\text{Air-borne}}{\sum_{k}} \mathrm{Q_k}(\omega) \cdot \left(P/Q(\omega)\right)_k \qquad (1)$$

where P(ω) is the total interior noise pressure at a target location, e.g. driver's outer ear (DOE). F(ω) are the operational forces at the passive side of the structure-borne transmission paths and Q(f) are the operational acoustic loads of the air-borne sources. The terms P/F and P/Q are the noise transfer functions (NTF). Same idea may be applied to vibration responses for e.g. steering wheel or seats comfort studies. All responses are given in frequency domain

Although TPA results in a relatively simple mathematical formulation for coherent systems, TPA for road induced noise is a multi-reference problem from, at least, four separate and uncoherent sources, acting simultaneously. Thus, the combination of multiple coherence techniques, principal component decomposition techniques, operational shape analysis, multi-reference transference transfer path analysis and vibro-acoustic modal analysis are candidate techniques in the process of performing good quality TPA and aiding the decision making process of enhancing products performances [3].

A full system TPA in a conventional approach demands a large number of sensors and channels, as well as relatively long measurement campaigns. Therefore, this paper presents a study on a faster, in-laboratory measurement that furnishes relevant information with respect to road noise. The next session present a short review on operational and in-laboratory TPA. In session 3, the case study is presented and the role of different tires in the Road NVH is discussed. Session 4 present the TPA-based solutions and, finally, some general conclusion are drawn in session 5.

ON-ROAD AND IN-LABORATORY MEASUREMENTS

There are different TPA methods available today. As the present road noise case relates to low frequency, the main contribution should be related to structure-borne noise and so, the focus is on how to calculate chassis to body structural loads and transfer functions. A briefly overview on structural approaches is presented in this paper. Figure 1 indicates approximately the percentage contribution of structure and air-borne noise as a function of frequency [4].

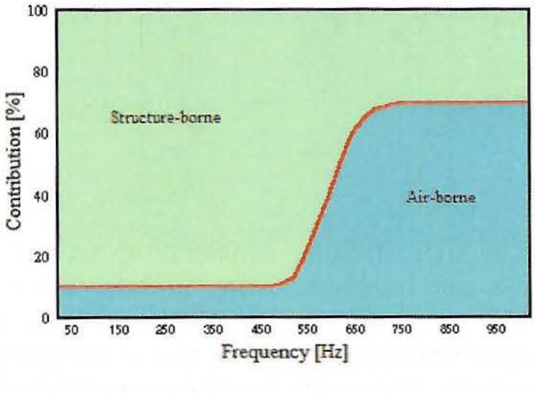


Figure 1 -: Contribution of Structure and Air Borne in frequency domain

Regarding mechanical load measurements, it can be separated into direct and indirect force methods. Direct operational force measurements by means of force transducers are very difficult due the need of vehicle disassembling to board fixtures and sensors. After all equipment set-up, the vehicle behavior can be easily affect, not mentioning the investments needed for dedicated load cells to each chassis architecture. In practice, it is only relevant for rig measurements, target data and CAE load models as seen in Hybrid TPA [5]. Therefore, indirect methods have been developed [1, 6].

The stiffness method or mount stiffness method uses Hooke's law to determine the operational forces at mounts and bushes from three-dimension dynamic stiffness and respective displacements. In general, the dynamic responses across the mounts are captured by accelerations in active and passives which are integrated twice to obtain the relative displacements. This indirect method is commonly used on Powertrain TPA cases.

$$f(t) = k_{dyn} \cdot \left(x(t)_{active} - x(t)_{passive}\right) \tag{2}$$

$$f(t) = k_{dyn} \cdot \left\lfloor \iint (\ddot{x}(t)_{active}) dtdt - \iint (\ddot{x}(t)_{passive}) dtdt \right\rfloor \tag{3}$$

In frequency domain, eq. (3) is expressed as:

$$F(\omega) = k_{dyn} \cdot \left[\frac{1}{\omega^2} \ddot{x}(\omega)_{active} - \frac{1}{\omega^2} \ddot{x}(\omega)_{passive} \right] \tag{4}$$

The Inverse Matrix Method, also known as Impedance Matrix method and Accelerance Matrix, is the most applied in Road TPA and used in this investigation. The method, based on reciprocity for MIMO systems theory, determines the operational forces from operational vibrations measured at the passive side (body) and transfer functions measured in the laboratory. Acceleration or velocity, as used in this case, is measured at force input locations under operation. The body is impacted at a series of different locations as close as possible from the operational force input locations. To use the classical impact hammer test, some components of the chassis need to be disconnected, depending on the locations under investigation. This point mobility test can be interpreted as a measure of how much acceleration or velocity exists at a hard point motion/deformation for a given force, at each frequency. This process results in a linear matrix equation (5) relating the vehicle vibration under operation with each individual impact test:

$$\begin{Bmatrix} f_1 \\ \cdots \\ f_n \end{Bmatrix}_{OP} = \begin{bmatrix} \frac{\dot{X}_{11}}{F_1} & \frac{\dot{X}_{12}}{F_1} & \cdots & \frac{\dot{X}_{1n}}{F_1} \\ \frac{\dot{X}_{21}}{F_2} & \frac{\dot{X}_{22}}{F_2} & \cdots & \frac{\dot{X}_{2n}}{F_2} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\dot{X}_{m1}}{F_n} & \frac{\dot{X}_{m2}}{F_n} & \cdots & \frac{\dot{X}_{mn}}{F_n} \end{bmatrix}_{FRF}^{-1} \begin{Bmatrix} \dot{x}_1 \\ \cdots \\ \dot{x}_m \end{Bmatrix}_{OP.passive} \tag{5}$$

The number of impact tests should be higher than the number of operational forces to be estimated. This gives an over determined system which can be solved using at least squares technique like singular value decomposions (SVD). The possible inaccuracies in the FRF matrix measurements (propagated during the inversion) as well as in the operational vibration vectors can lead to the amplification of numerical errors in the force estimation. As a control parameter, to quantify the influence of matrix inversion, the condition number method is very useful. The condition number describes how errors in the input data relate to errors in the determined forces. Using SVD, a condition number can be obtained from the ratio between the lowest and the highest singular values for rectangular matrices.

Finally, the body sensitivity of noise or vibration response to forces inputs are measured using also the impact hammer method. Indeed, by adding microphones or accelerometers (targets) inside the vehicle during point mobility tests, one can simultaneously determine the NTFs and FRFs reciprocally, saving measurement time.

Depending on the TPA approach, the transfer matrixes can be measured either in trimmed body or full vehicle conditions.

Regarding the accurate correlation between measured and calculated noise, the use of indirect techniques for load estimation FRF and NTF, leads to a significant problem: the time needed to measure all subsystems local three-dimension FRF matrixes. Therefore, whenever possible, reduced approaches may be considered, discarding the impact of cross-coupling effects between some interface locations. This approach results is a simplification of the in-theory full FRF matrix to a block diagonal matrix, consisting only of cross-FRFs on the same subsystem, or even a full diagonal matrix, considering only the local impedance. However, each case must be analyzed with care, considering that the simplification is taken the higher is the introduced errors on the load estimation, mainly in the full-diagonal approach. [1]. The Reduced Matrix Method, which uses a full diagonal matrix, is demonstrated in Eq.(6):

$$\begin{Bmatrix} f_1 \\ \dots \\ f_i \end{Bmatrix}_{OP} = \begin{bmatrix} \frac{\dot{X}_{11}}{F_1} & 0 & \dots & 0 \\ 0 & \frac{\dot{X}_{22}}{F_2} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \frac{\dot{X}_{ii}}{F_i} \end{bmatrix}_{FRF}^{-1} \begin{Bmatrix} \dot{x}_1 \\ \dots \\ \dot{x}_i \end{Bmatrix}_{OP\ passive} \tag{6}$$

In principle, the weaker the coupling between two subsystems, the lower is the impact on their cross-coupling terms. The opposite is valid to strong coupling. When force estimation fails due to strong coupling, the related NTFs will not present good results – e.g. for chassis mounts and weak body structures [6].

ROAD NOISE TPA

The case started during the tires development phase on a representative prototype. Then, it was identified that a different sound quality behavior was present for a specific tire model. Treated as a road induced rumble, the unpleasant and deep low frequency rolling sound is most noticeable in low speed on smooth road tracks. The motivation behind this study is to understand and avoid the road booming from auto-maker point of view, guaranteeing the same noise balances for all tire models available. The goal is optimize components to absorb tire vibrations without changing vehicle dynamics behavior. The graphic on Fig.2 presents the sound pressure level at driver's outer ear position for three different tire models in a cruise condition.

Subjective evaluations and laboratory listening sessions confirmed that the noise problem of sample named as "Tire A" is around 180 Hz. As highlighted in [7], it is quite difficult and not reasonable try to identify subjectively the structural noise sources by directivity impression (e.g. body panels or chassis components behaviors) initiated on the primary source, i.e. by the worst tire/road interaction. However is acceptable to try to understand where the critical paths are. For this investigation, the same tire sets were assembled in different positions between axles. Subjectively, this exercise leads to the conclusion that the main paths came exclusively from the front suspension interaction, when the worst tire model is assembled there.

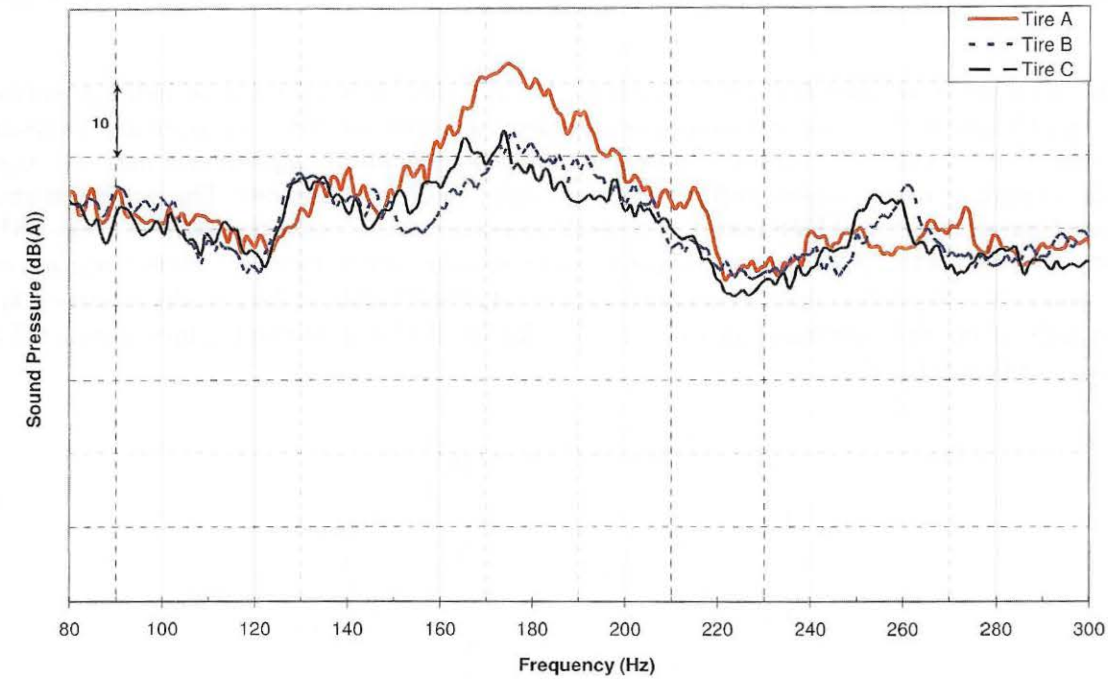


Figure 2 - : Sound Pressure Level of tires models and the road induced rumble (red/continuous line)

In order to reduce tire booming response, the input force locations were strategically chosen to be indirect measured on the TPA process. Considering the front suspension geometry symmetry (Mc Pherson type - Fig.3), the measurements were taken into only one side of front suspension, reducing the road and laboratory test time.

To reduce the complexity of the TPA session and the number of sensors needed the cross-coupling effects were discarded by adopting a Reduced Matrix method. After a careful analysis of the input forces in the front suspension, predicting the possible actions which could be taken into the chassis, three principal components have been defined: the shock tower attachment and A-arm bushings (point #3 and point #4 in Fig.3).

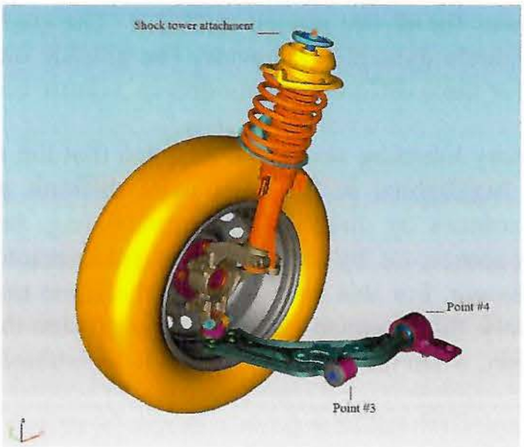


Figure 3 - : Input force locations (principal components) to Road TPA

The operational measurements to the indirect force estimation were done simultaneously to the internal sound pressure level acquisition, again with the microphone at the DOE position in the same cruise conditions evaluated before. The test was performed with the engine turned off to ensure a better interior noise correlation. To consider both sides of the front suspension contribution, the summation of incoherent sound sources were doubled. Figure 4 shows the correlation between the noise measured at the DOE, the contributions form the Points #3, #4 and Top Mount and the calculated overall noise based on the as the critical path observed.

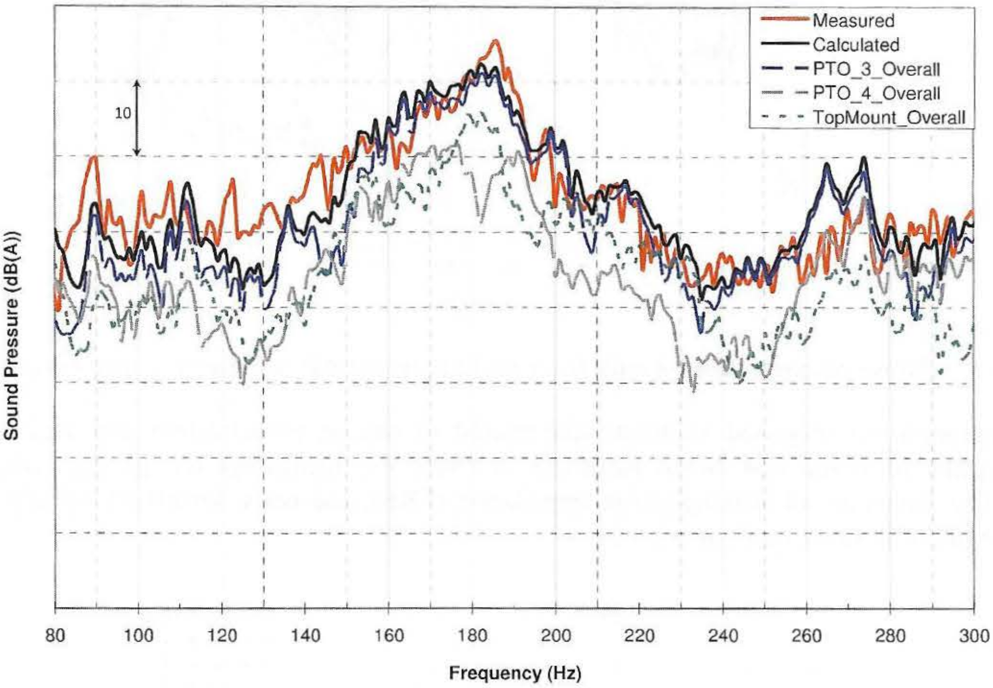


Figure 4 - : Noise correlation and principal components contribution

FORCES & SENSITIVITY

As seen, the selected principal components for one side of front suspension and the Reduced Matrix method provided a good correlation to the measured noise in this case study. Once the A-arm front bushings (Point #3) were identified as the critical path, two scenarios were developed in view of reducing the road rumble noise: (i) new option of tire model and (ii) bushings 10% softer. To find the best solution in terms of both, performance and cost, is not a simple task, once it depends on a series of particular attribute tradeoffs, the program timing, and pay-back investment strategy.

As seen in Fig. 5 the A-arm front bushing is the critical path for the sum of calculated rumble phenomena. Decomposing the overall noise into axles coordinates, the y and z axles presented to be the most import noise contributors and are related to the radial bushing response. The Fig. 6 presented is the respective forces responses. Although the y and z noise paths, the y direction has the highest force amplitude contribution.

Thus the rumble noise perception is summarized to y responses of tire/road interaction and the noise response of the body in y and z directions. In the same way that TPA approaches allows breaking down the load location and the respective NTF, the possible solutions can be targeted into chassis (point #3) forces or body sensitivity.

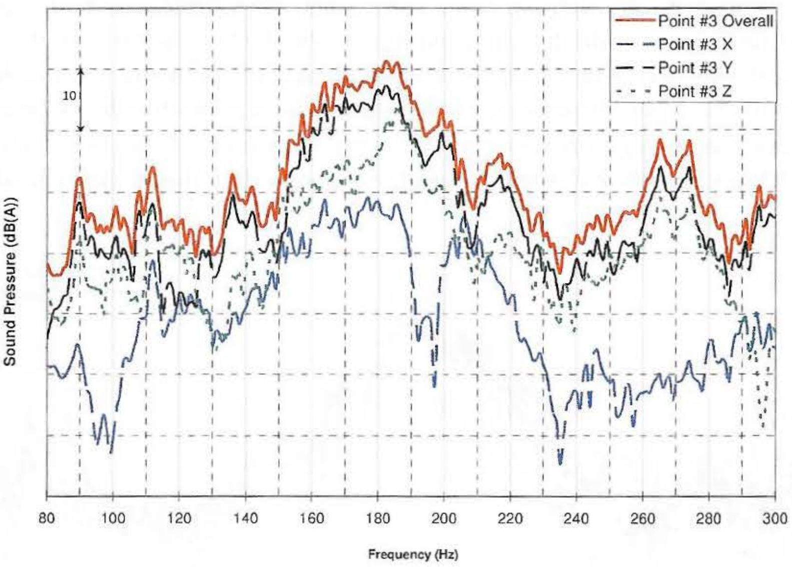


Figure 5 - : Noise response from A-arm front bushing (point #3), and the x, y and z directions.

As already mentioned the proposed solutions are related to chassis modification and were evaluated and presented by means of Force and Noise Response at Point #3, measuring the passive velocity for each configuration. The functions of driving point impedance (FRF) and body sensitivity (NTF) are the same regardless of the tire or bushing configurations.

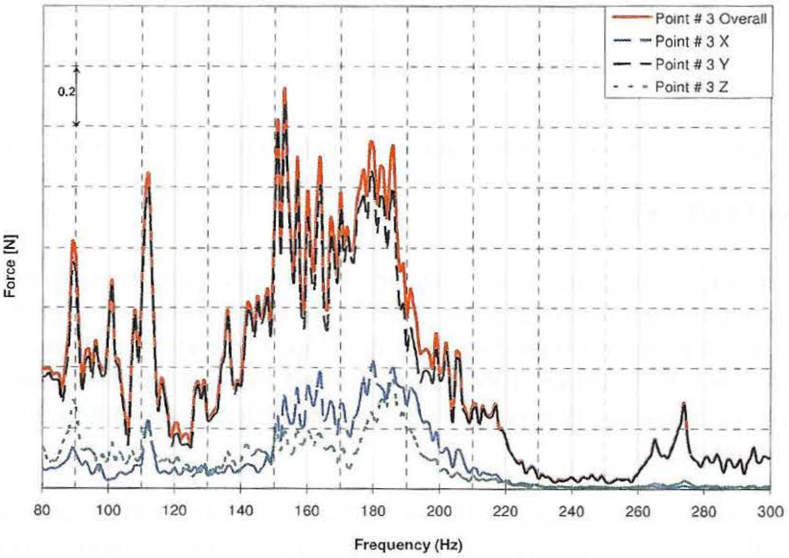
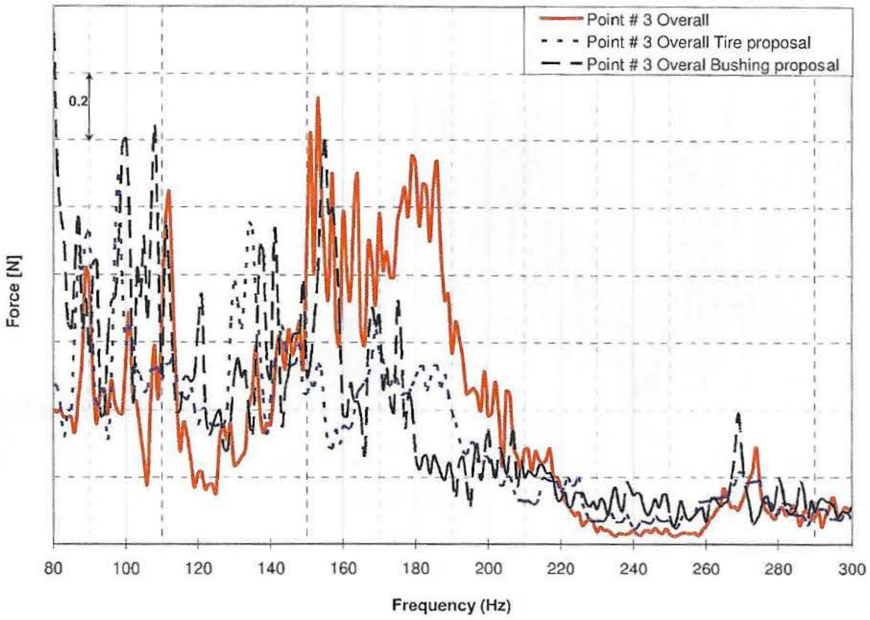
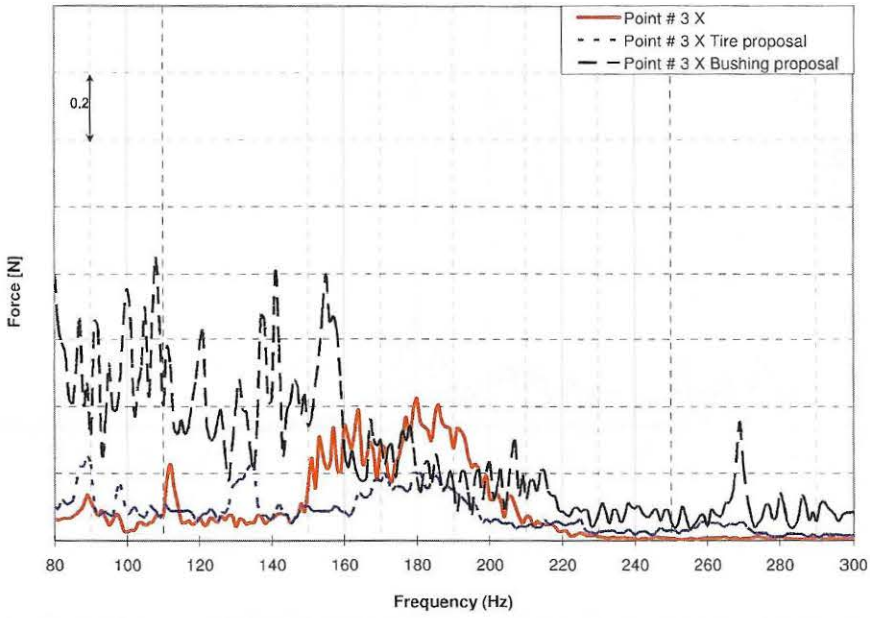


Figure 6: Force response from A-arm front bushing (point #3), and the x, y and z direction.

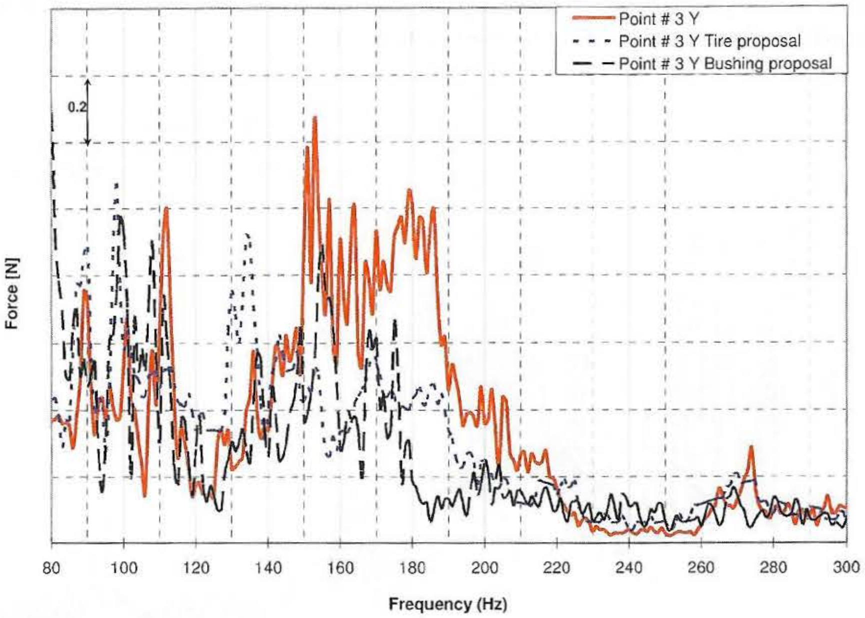
Finally the Figures 7 and 8 show the forces and noise responses of the both proposals are lower than the initial condition, around 180Hz. However, as can be seen in Fig 7(b) the softer bush presented higher force on the x axle for lower frequencies. Probably, it is associated to the non-linearity of the rubber bushing movements in the imminence of strike through occurrence. Although, the overall results of forces and noise responses for both proposals is considered satisfactory regarding to road rumble noise.



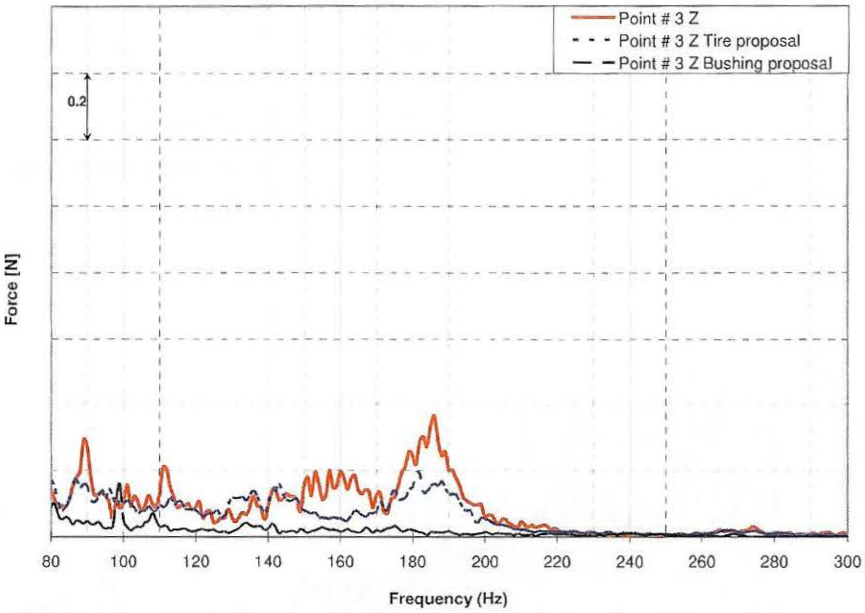
(a)



(b)

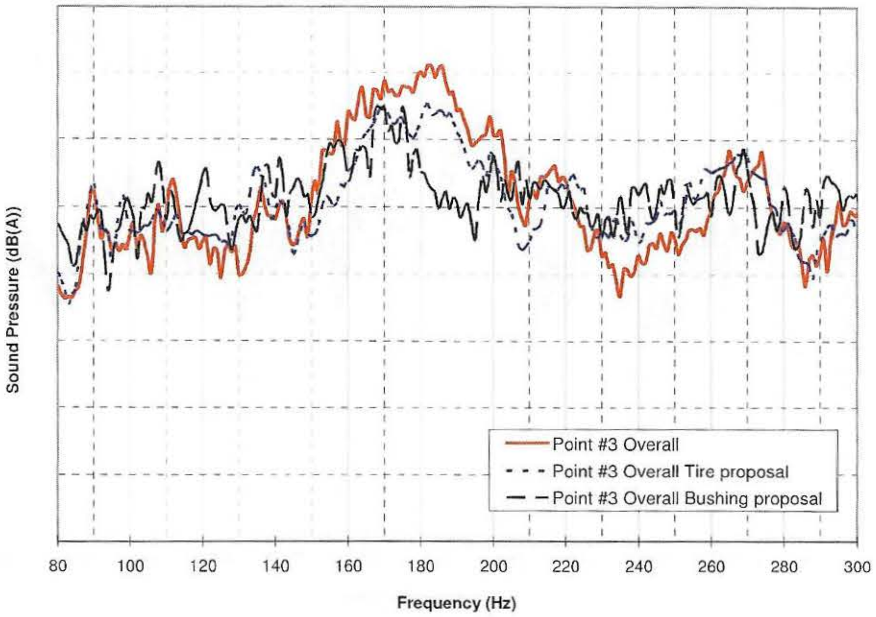


(c)

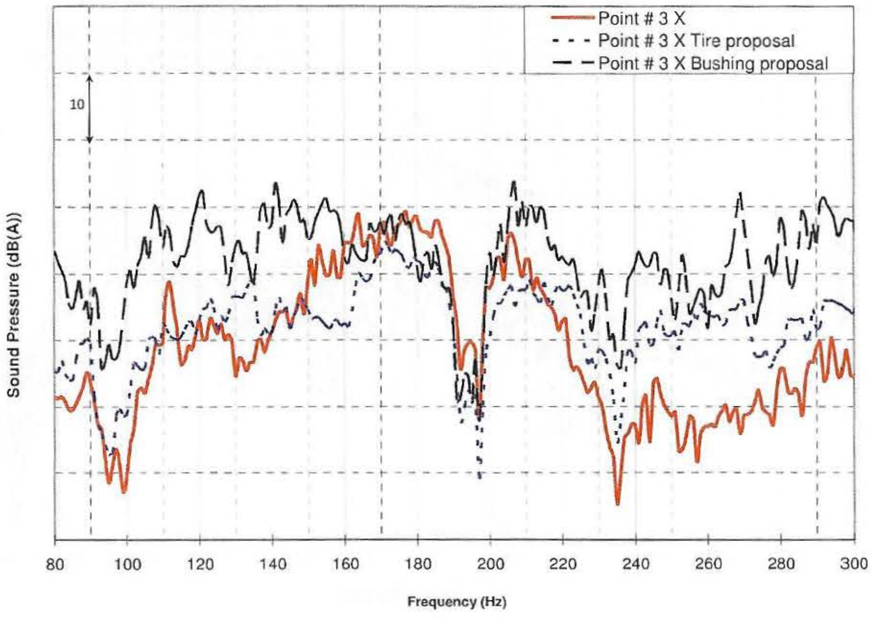


(d)

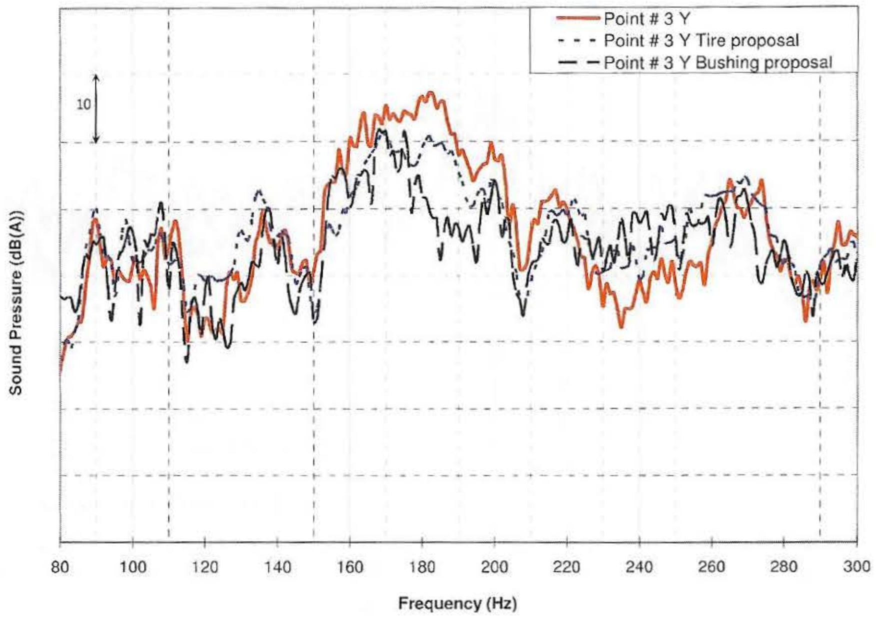
Figure 7 - : Comparison of the force response from each proposed solution- (a) Overall, (b) x-direction, (c) y-direction and (d) z-direction.


Sound Pressure (dB(A))
Point #3 Overall
Point #3 Overall Tire proposal
Point #3 Overall Bushing proposal
80
100
120
140
160
180
200
220
240
260
280
300
Frequency (Hz)

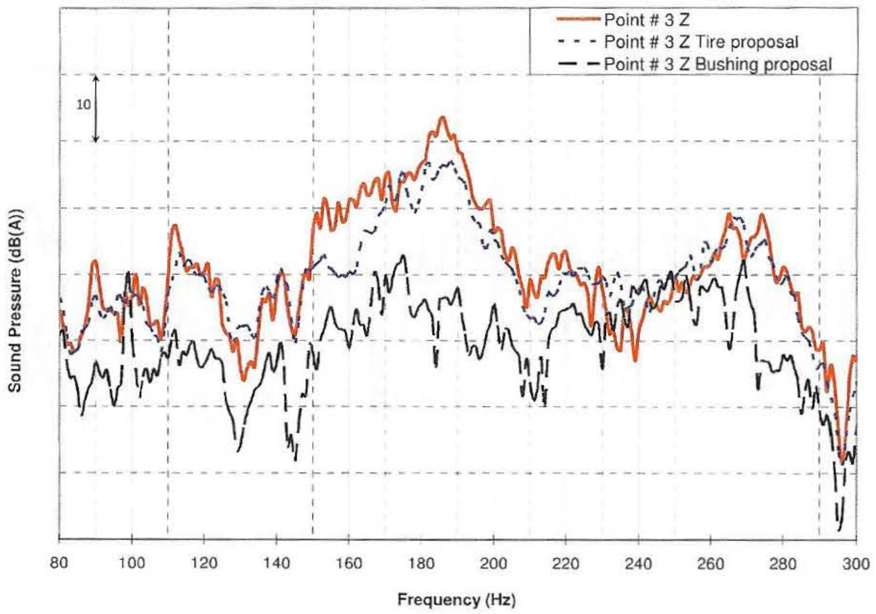
(a)


Point # 3 X
Point # 3 X Tire proposal
Point # 3 X Bushing proposal
10
Sound Pressure (dB(A))
80
100
120
140
160
180
200
220
240
260
280
300
Frequency (Hz)

(b)



(c)



(d)

Figure 8 - : Comparison of the noise response from each proposed solution- (a) Overall, (b) x-direction, (c) y-direction and (d) z-direction.

CONCLUSIONS

The classical TPA methods are revised regarding the structural-borne road noise implication of a multiple reference problem for uncoherent sources. The case study presents a particular and unpleasant noise response around 180 Hz from a specific tire model which results in a road noise unbalance for this prototype. From the auto-maker point of view, TPA is conducted to investigate the chassis components contribution.

As the subjective evaluations indicated that the main contributors were in the front suspension paths, the measurement was concentrated on the three principal components of the McPherson system (A-arm bushings and top mount) in one side of the car, assuming suspension geometry symmetry.

Further more, in view of reducing the number of sensors and channels, as well as the measurement time, instead of measuring the full FRF matrix, a diagonal Impedance Matrix was used instead. This simplification is based on the hypothesis that the cross-terms play a less important role an can, therefore, be neglected, which reduces the number of necessary measurements by discarding measurements of the off-diagonal terms.

Although many simplification hypotheses were assumed, the results presented in this paper are in good agreement with the measured and calculated noise. Therefore, this customized TPA analysis can be considered as a reasonable approach for pointing out critical paths as well as providing a reliable measure for the performance comparison of different scenarios. In particular for the presented case-study the use of the new tire set and bush #3 are possible solutions for the road induced noise.

As future work, the author of this paper are looking into the use of TPA a tool to understand the tradeoffs between NVH and ride/handling when specifying suspension elements such as bushings.

REFERENCES

1. Van der Auweraer, H., Mas, P., Dom, S., Vecchio, A. et al., "Transfer Path Analysis in the Critical Path of Vehicle Refinement: The Role of Fast, Hybrid and Operational Path Analysis," SAE Technical Paper 2007-01-2352, 2007, doi:10.4271/2007-02-2352.
2. Moller, N. and Batel, M., "Obtaining Maximum Value from Source/Path Contribution Analysis," SAE Technical Paper 2005-01-4183, 2005, doi:10.4271/2005-01-4183.
3. Wyckaert, K. and Van der Auweraer, H. “Operational Analysis, Transfer Path Analysis, Modal Analysis: Tools to Understand Road Noise Problems in Cars,” SAE Technical Paper, 1995, doi:10.4271/951251.
4. Ford Motor Company Road Noise internal course, 2008.
5. Kim, S.-J., Yang, H.-I., and Lee, S.-K., “Prediction of Interior Noise Based on Hybrid TPA,” *SAE Int. J. Passeng. Cars - Mech. Syst.* **2**(1):1440-1448, 2009, doi:10.4271/2009-01-2115.
6. Ford Motor Company INCA2_training module 05 - Structure-borne Contribution Analysis - Part 1: Theory and Methods
7. A.P. Dowling, J.E. Ffowcs Williams, Sound and Sources of Sound, Chambridge 1983 p 149

CONTACT INFORMATION

César Helou Teodoro da Silva
Ford Motor Company South America Operation - Tatuí Proving Ground.
Vehicle Engineering Team, NVH Engineer
KM 124, SP127 Highway
ZIP: 18276-860 - Tatuí, SP - BRAZIL
csilv219@ford.com

Alvaro Costa Neto, PhD
São Carlos School of Engineering - University of São Paulo
Av. Trabalhador Sancarlense 400
13566-590 São Carlos - SP, BRAZIL
costa@sc.usp.br

Leopoldo P.R. de Oliveira, PhD
São Carlos School of Engineering - University of São Paulo
Av. Trabalhador Sancarlense 400
13566-590 São Carlos - SP, BRAZIL
leopro@sc.usp.br

ACKNOWLEDGMENTS

The author would like to thank all the engineers from Ford Motor Company involved in this case study.

ISSN 0148-7191

SAE Customer Service:
Tel: 877-606-7323 (inside USA and Canada)
Tel: 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
SAE Web Address: http://www.sae.org
Printed in USA

SAE International