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Structure-borne road noise prediction using component-based TPA

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ABSTRACT

Road induced noise is getting more and more significant in context of the electrification of the powertrain. Due to the current trends emerging in the automotive industry (increased vehicle variants, shorter development cycles, …), technologies enabling full vehicle noise predictions from the individual source components are becoming very attractive. In this sense, Component-based TPA was derived, in order to predict the noise contribution of vehicle components early in the development process. In this method, source excitation is characterized by a set of equivalent loads, derived from test bench or in-situ measurements, that independently represent the source from any receiving structure. In this work, this methodology is validated on a tire-suspension system in static condition. The tire is characterized in a rig by a set of invariant input loads (i.e. blocked forces) identified at the spindle location. The blocked forces identified are used to derive the spindle contact forces, by means of frequency based substructuring (FBS). The estimated spindle forces are then combined with the receiving structure FRFs and used for road vibro-acoustic prediction. The proposed methodology allows to combine the existing components with other existing or simulated components without being physically assembled, allowing to streamline the vehicle development.

Keywords: Road Noise, Component Based Transfer Path Analysis, Blocked Forces
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1. INTRODUCTION

The evolution of the automotive industry towards EVs has led the tire-road interaction becoming one of the most dominant sources of noise within the vehicle cabin

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even at lower speeds due to reduced masking effect of the powertrain. In addition, the shortening of the development cycle, and the increased vehicle variants, have pushed the automotive industry to seek for technologies allowing to predict the (structure borne) road noise contribution in the early stage of the vehicle development process avoiding costly and time-consuming design iterations.

Computer Aided Engineering (CAE) solutions can help to accurately evaluate new vehicle designs, provided that the vehicle components (i.e. suspension, vehicle body,…) are accurately modelled, and invariant inputs models are correctly identified.

Invariant inputs are quantities providing unique description of the source component for a specific operating condition. These quantities are therefore considered characteristics of the tire, and independent of the suspension and body characteristics.

Several approaches have been explored in literature aiming to characterize the tire excitation for vehicle interior noise predictive engineering. Spindle forces derived from full vehicle road measurements have proven to provide high accuracy prediction results for a specific vehicle and suspension configuration. However these forces cannot be transferred to other configurations, since spindle contact forces are highly dependent on the full vehicle assembly, since tire and suspension are strongly coupled. An alternative approach based on inverse road surface identification has been developed to overcome the dependency of the spindle forces [1]. The results indicated that the road input still has some dependencies on the tire characteristics.

Another approach consist of directly measure the spindle forces on a test cell using a load sensor. To ensure a correct blocked force measurement, the test cell should be much more rigid compared to the tire wheel assembly. This assumption is particularly difficult to meet in certain application cases due to the dynamic modal behavior of the test cell affecting the load measurements starting from 150Hz [2].

This paper presents the identification of a set of invariant input loads (i.e. blocked forces) identified at the spindle location. By definition the blocked forces are characteristic of the tested source component (e.g. tire wheel assembly) as if the spindle is “blocked”, and they are therefore independent of the dynamic behavior of the suspension or vehicle to which the tire is mounted. The identified blocked forces allow to perform vehicle interior noise prediction without the physical availability of the vehicle. This technology allows to perform predictive engineering for different vehicle and suspension variants. Moreover, for a tire supplier, the correct identification of the blocked forces represents a criteria to obtain realistic tire target settings.

This paper shows the application of the component based TPA on a tire-suspension test rig with the tire in no rolling condition. The Coriolis and the centrifugal force effects are excluded from this analysis. The blocked forces identified on the rig are used to derive the spindle contact forces, by means of frequency based substructuring (FBS). Comparison of the spindle contact forces results obtained by inverse identification on the full tire-suspension system and derived from blocked forces will be assessed in this paper.

2. ROAD NOISE SYNTHESIS USING COMPONENT BASED TPA

2.1 Theory of component based TPA

The source characterization described by invariant loads clearly differentiate the classical TPA from the component based TPA. The former identifies the contact forces that are transmitted between the source and the receiver [3]. Contact forces are dependent on the assembled system and can in general not be transferred to different receivers, since the contact force depends on the source and receiver of the system. Therefore contact forces cannot be used for predictive engineering analysis: especially in cases of strongly coupled systems.

Let's assume a system composed of two components: a source A and a receiver B, as schematically shown in fig.1. The contact forces (F_{r2}) identified at the connection between the two components can be identified using Equation 1.

$$F_{r2} = [H_{j3}^{B}]^{-1} \cdot u_j \qquad [1]$$

Where H_{j3}^{B} is the frequency response function matrix of the uncoupled receiver between the connection and any point j in the component receiver B.

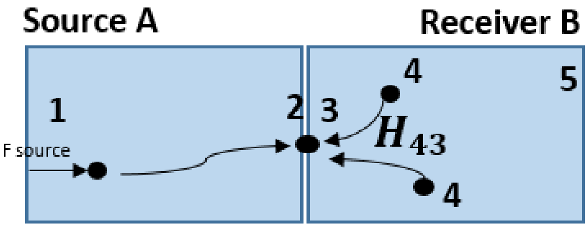

Figure 1: Schematic representation of an assembly system

Component based TPA is a relatively new TPA technique that allows to characterize a source component independently from the receiver structure by a set of blocked forces and to predict its behaviour when coupled to different receivers, allowing for a virtual vehicle assembly [4,5,6,7]. Blocked forces can be identified on a vehicle assembly (in-situ characterization), or from test rig experiments.

The blocked forces identified at the interface connections between the two components can be calculated using Equation 2.

$$F_{Blocked2} = [H_{j2}^{AB}]^{-1} \cdot u_j \qquad [2]$$

Where H_{j2}^{AB} is the frequency response function matrix of the coupled system between the connection and any point j in the component receiver B. Alternative ways to characterize the source in blocked condition or in free-free are described in literature [4,6], but they will not be discussed in this paper.

In a next step these identified blocked forces, combined with coupled FRFs, allow to predict the final total contribution in the vehicle without having to physically integrate the source. Coupled FRFs can be experimentally measured, if the assembly is physically available. Alternatively, when only the components are available, or even only partially available, FBS (Frequency Based Substructuring) is applied to calculate the FRFs of the coupled setup starting from the FRFs of the uncoupled source and receiver. FBS allows to combine components experimentally measured or obtained from numerical models.

2.2 Frequency Based Substructuring

To couple individual components A and B into an assembly AB, each component can be described by means of its FRF system matrix. When components A and B are rigidly coupled into assembly AB, the FRFs of the coupled structure can be calculated using the dual assembly formulation / Lagrange Multiplier FBS in Equation 3 [8,9,10].

$$H^{AB} = \begin{bmatrix} H_{11}^{A} & H_{12}^{A} & 0 \\ H_{21}^{A} & H_{22}^{A} & 0 \\ 0 & 0 & H_{44}^{B} \end{bmatrix} - \begin{bmatrix} H_{12}^{A} \\ H_{22}^{A} \\ -H_{43}^{B} \end{bmatrix} \cdot [H_{22}^{A} + H_{33}^{B}]^{-1} \cdot \begin{bmatrix} H_{12}^{A} \\ H_{22}^{A} \\ -H_{43}^{B} \end{bmatrix}^{T} \qquad [3]$$

Considering the FBS equation combined with Equation 2, the responses at any point in the receiver structure can be predicted using the blocked forces identified at the interface connections, as in Equation 4.

$$u_j = \left[H^B_{j3} \cdot [H^A_{22} + H^B_{33}]^{-1} \cdot H^A_{22}\right] \cdot F_{Blocked2} \quad [4]$$

By combining Equation 1 and Equation 4, Equation 5 is derived showing the relation between blocked forces and contact forces.

$$F_{r2} = [H^A_{22} + H^B_{33}]^{-1} \cdot H^A_{22} \cdot F_{Blocked2} \quad [5]$$

When assembling FRFs experimentally measured from individual components, the process puts high demands towards data quality during the component characterization ensuring free-free condition at the boundaries, since 'direct' FBS theory assumes the components to be fully decoupled.

A schematic representation of the substructuring approach applied to the tire and suspension assembly is presented in Figure 2.

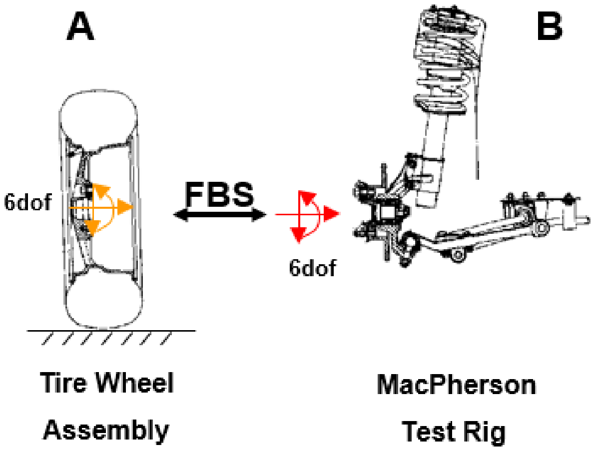

Figure 2: Substructuring applied to the Tire Wheel and MacPherson suspension Test Rig

2.3 Geometrical reduction

The coupling of the components using FBS and blocked forces calculation usually requires the access to input and output DOFs that cannot be directly measured, whether because of feasibility issues or simply non-existence of the material point, as the case of the spindle location. Moreover, coupling of components requires a finite number of DOFs including translational and/or rotational DOFs. For the above reasons, geometrical reduction has been applied. Geometrical reduction [11,12] (also called Virtual Point transformation) relies on the main assumption that the surrounding region of the point of interest is assumed to exhibit a rigid modal behavior, creating a rigid body dependence between the DOFs contained by the region. Multiple excitation and responses are measured in the close vicinity to the point of interest to be reduced. The 6 DOFs of the force vector due to the kth applied force acting on the rigid body is shown in Equation 6.

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ M_{xx} \\ M_{yy} \\ M_{zz} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -z_{c_k} & y_{c_k} \\ z_{c_k} & 0 & -x_{c_k} \\ -y_{c_k} & x_{c_k} & 0 \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}_k \quad [6]$$

Where x_{ck}, y_{ck} and z_{ck} are the coordinates of impact point k relative to a coordinate system whose origin is at the point of interest c.

A similar reasoning can be applied to the response DOFs. The 6 rigid body modes consist of rigid body translations in the x, y and z directions and rigid body rotations around the x, y and z axes whose origin is located at point c. Equation 7 shows the relation between the 6 rigid body modes and a set of translational response points k.

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}_k = \begin{bmatrix} 1 & 0 & 0 & 0 & z_{c_k} & -y_{c_k} \\ 0 & 1 & 0 & -z_{c_k} & 0 & x_{c_k} \\ 0 & 0 & 1 & y_{c_k} & -x_{c_k} & 0 \end{bmatrix} \begin{bmatrix} a_x \\ a_y \\ a_z \\ R_{xx} \\ R_{yy} \\ R_{zz} \end{bmatrix} \quad [7]$$

Where x_{ck}, y_{ck} and z_{ck} are the coordinates of response point k relative to a coordinate system whose origin is at the point of interest c.

From the reduction of forces and accelerations in the point of interest, a new set of reduced FRFs at the spindle is obtained.

3. EXPERIMENTAL TEST SETUP

The test setup, composed of a tire-suspension test-rig, located at the Katholieke Universiteit Leuven (KUL), was used to validate the methodology. The setup consisted of a tire wheel assembly connected to a MacPherson strut suspension mounted on support frame, as shown in Figure 3. The tire was excited using a shaker reproducing a road profile in the vertical direction. The tire was measured in static condition: the rolling effect was not included in the objective of this test campaign.

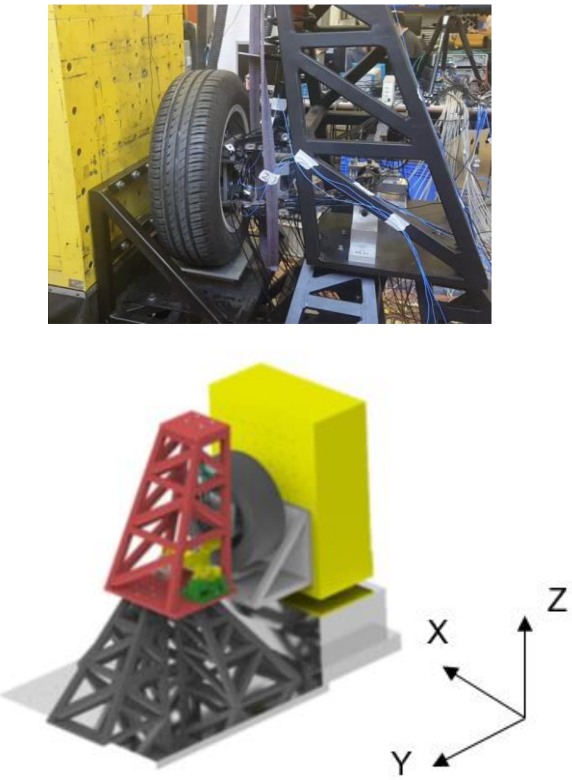

Figure 3: Tire-suspension experimental setup [13]

3.1 Experimental procedure for spindle load identification: contact forces and moments

Identification of the spindle contact forces requires geometrically reduced decoupled FRFs measurements from spindle to responses in the receiver, and a set of operational receiver responses measured during operating condition, when the tire-suspension is exposed to the road profile excitation.

FRFs measurements were performed using a calibrated LMS Qsource integral shaker exciting the frequency range from 30Hz to 300Hz.

The procedure for spindle contact force identification is schematically presented in Figure 4.

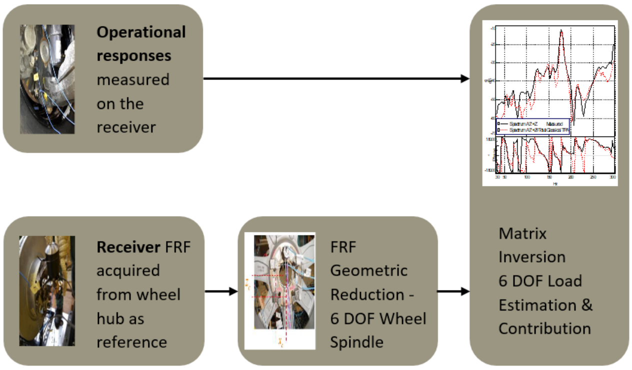

Figure 4: Schematic representation of the procedure for spindle contact forces and moments identification

3.2 Experimental procedure for invariant spindle load identification: blocked forces and moments

Identification of the blocked forces at the spindle requires geometrically reduced coupled FRF measured from spindle to responses in the receiver, combined with the operational receiver responses measured during operating condition using the same road profile excitation as in paragraph 3.1. The blocked forces were identified in an inverse way on the tire-suspension test rig.

Coupled FRFs measurements were performed using a calibrated LMS Qsource integral shaker exciting the frequency range from 30Hz to 300Hz.

The procedure for spindle blocked force and moments identification is schematically presented in Figure 4.

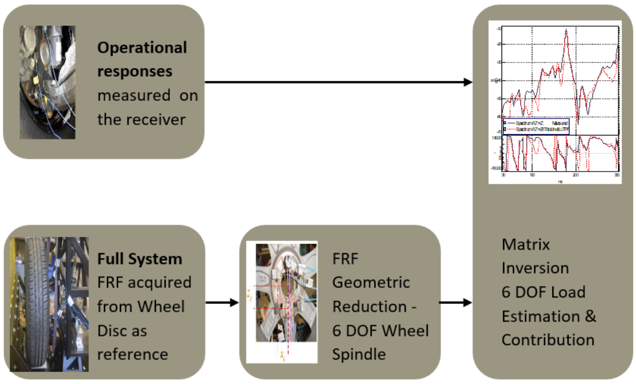

Figure 5: Schematic representation of the procedure for spindle blocked forces and moments identification

3.3 Procedure for experimental substructuring of the Tire-Suspension Setup

As presented in paragraph 2.2, experimental substructuring requires the components to be fully decoupled. Figure 6 shows the experimental procedure to measure decoupled FRFs of the tire-wheel assembly (source) and of the MacPherson suspension (receiver). During the FRFs measurements, the tire-wheel and the suspension were preloaded with a preload as close as possible to the one used during the operational tests. In this way the same interface stiffness and damping as in coupled tire-suspension assembly were ensured.

Experimental substructuring allowed to derive the spindle contact forces and moments from the identified spindle blocked forces and moments.

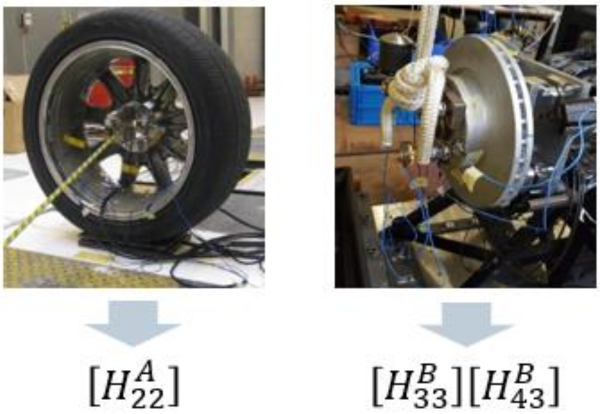

Figure 6: Experimental procedure to measured decoupled FRFs of the tire-wheel assembly (on the left) and of the suspension (on the right)

4. EXPERIMENTAL RESULTS AND VALIDATION

In this section the results obtained for the spindle forces identification will be presented. Two approaches have been used: classical TPA and component based TPA. Finally the comparison of the spindle contact forces contributions derived from Classical TPA and from blocked forces using FBS will be presented validating the FBS approach.

4.1 Classical TPA: Contact Force Contribution Setup Setup

Applying matrix inversion TPA using the receiver transfer functions only, results in the spindle contact forces estimation. During the inversion appropriate truncation was applied. Knowing these loads one can determine the contributions of these loads to each of the sensor locations on the receiving side of the test rig using:

$$u_j = \sum_i H_{ji}^{B} F_{r\,i} \qquad [8]$$

These contribution results are used to validate the TPA approach. The results shown in Figure 7 indicate that the total predicted acceleration correlates very well with the measured response on a point in the lower control arm. The deviation of the predicted response from the target below 50Hz could be related to stick-slip effect of the suspension or difference in preload between operational & FRF testing conditions. For sake of clarity the contribution of the moment around the axis of rotation of the tire-wheel (y axis) has been excluded from the contact force identification considering that this degree of freedom was not constrained and therefore resulting in a very low contribution to the target.

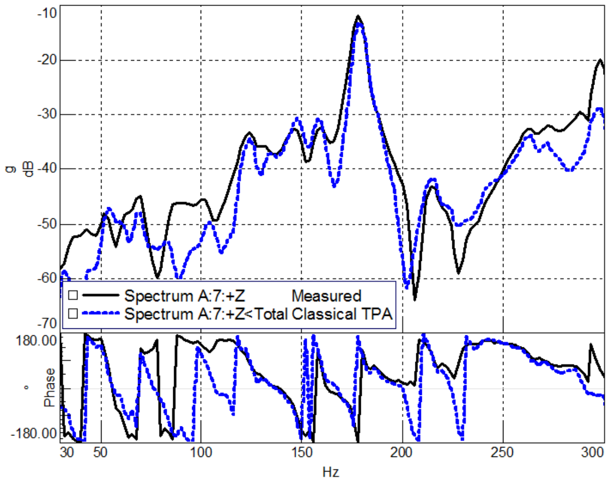

Figure 7: Comparison between measured target (black curve) and predicted total contribution obtained from Classical TPA (blue dotted curve)

Figure 8 shows the total and the partial contribution results for the analyzed target. Starting from the top row to the bottom, the measured target, the total contribution, the partial contributions of the spindle moment around x axis, and of the moment around the z axis, and the partial contributions of the spindle forces in x, y, and z are presented.

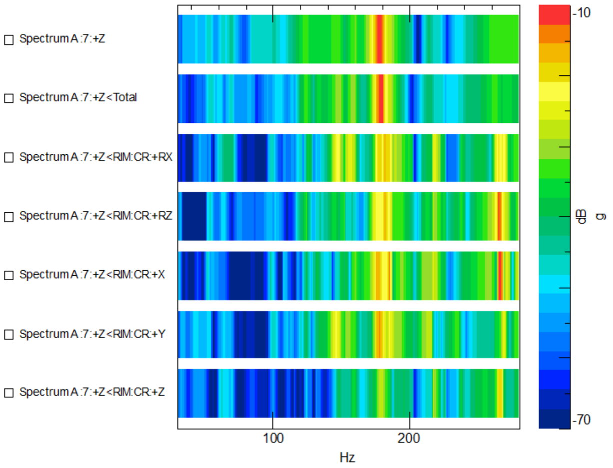

Figure 8: Partial contribution analysis results from the classical TPA for the analyzed targets

4.2 In-Situ TPA: Blocked Forces Contribution

Blocked forces have been identified by inverting the coupled FRFs matrix of the tire-suspension system. The moment around the y axis has been excluded from the inversion and truncation was applied. Using these the total contributions at the sensor locations are calculated:

$$u_j = \sum_i H_{ji}^{AB} F_{Blocked\ i} \qquad [9]$$

The total contribution prediction of the in-situ TPA shows a very good agreement with the measured response acceleration at the target, validating the in-situ TPA approach, as shown in Figure 9.

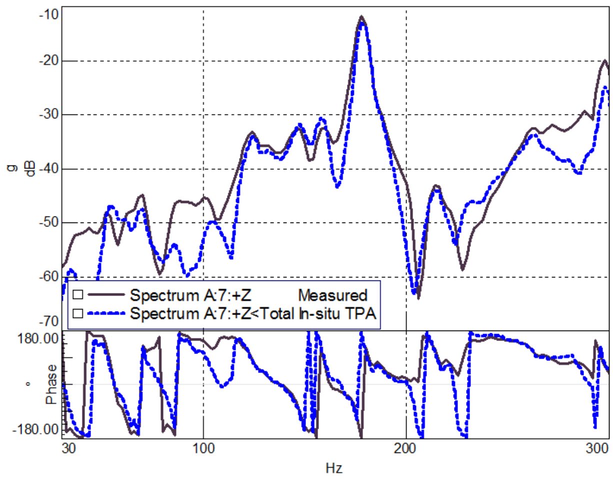

Figure 9: Comparison between measured target (black curve) and predicted total contribution obtained from in-situ TPA (blue dotted curve)

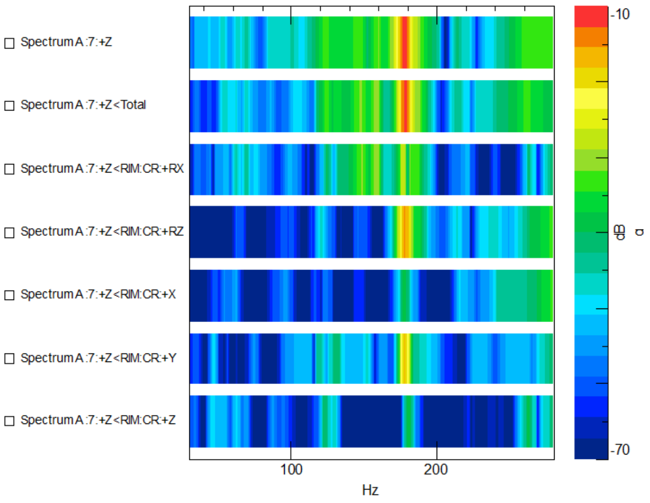

Figure 10: Partial contribution analysis results from the in-situ TPA for the analyzed target

Figure 10 shows the total and partial contribution results for the analyzed target. As for classical TPA, the predicted total contribution correlates well with the measured target. The partial contributions from in-situ TPA largely differ from the ones obtained from classical TPA. This is to be expected since they have to be interpreted in a different way as depicted in Table 1.

Table 1: Interpretation of Classical and In-situ contributions [14]

	Load	**Transfer**
Classical TPA	Contact Force Mixed Property	Receiver Property
In-situ TPA	Blocked Force Source Property	Mixed Property

4.3 Component Based TPA using FBS

Frequency Based Substructuring has been used to retrieve the spindle contact forces and moments from the identified blocked forces, as presented in Equation 5. During the FBS inversion appropriate truncation was applied. Five DOFs coupling between the tire and the suspension have been used, excluding the moment around the tire rotational axis.

Figure 11 shows the predicted acceleration using the spindle contact forces derived from identified blocked forces. The comparison with the measured response shows a good agreement validating the methodology.

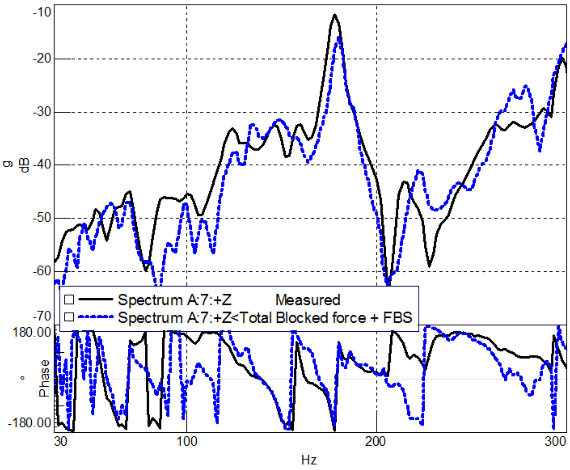

Figure 11: Comparison between measured target (black curve) and predicted total contribution obtained from spindle blocked forces combined with FBS (blue dotted curve)

Finally, Figure 12 presents the partial contribution analysis results. Comparing these results with the ones obtained from classical TPA (Figure 8), a good agreement between the partial contributions can be noticed, which validates the capability of deriving contact forces from blocked forces using FBS. Deviations in the contribution results can be noticed starting from 250Hz due to possible violation of the rigidity assumption in the FRF geometrical reduction step.

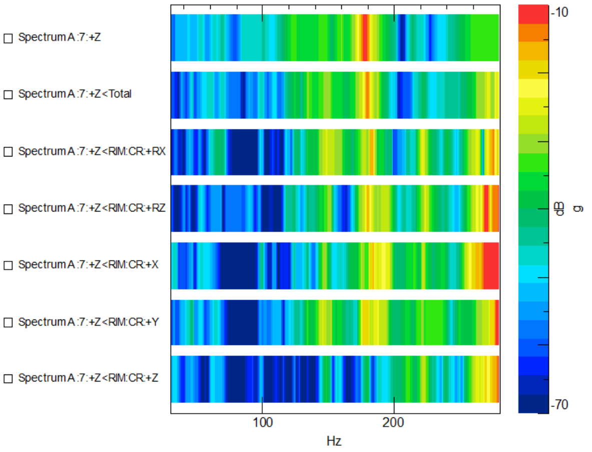

Figure 12: Partial contribution analysis results from component based TPA combined with FBS for the analyzed target

5. CONCLUSIONS

This paper presents and validates a methodology to identify a set of invariant spindle loads (i.e. blocked forces) on a tire-suspension test rig. The invariant loads, identified on an assembly configuration by inverting the coupled FRFs matrix, proved to be able to correctly predict the response on targets located on the receiver. This result can be extended to any target located in the receiver structure.

In addition, the blocked forces identified on the tire-suspension test rig were used to derive the spindle contact forces, by means of frequency based substructuring FBS. Comparison of the spindle contact forces derived from classical TPA and from blocked forces showed a very good agreement demonstrating the validity of the FBS for the setup under investigation with the tire in no rolling condition. Future investigations will include the rolling effect of the tire in the prediction analysis.

Moreover, validation of the use of the identified blocked spindle forces for predictive engineering analysis has not been assessed in this paper. The prediction analysis for a modified suspension will be objective of investigation in the near future.

6. ACKNOWLEDGEMENTS

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