VI Congreso Iberoamericano de Acústica - FIA 2008
Buenos Aires, 5, 6 y 7 de noviembre de 2008

FIA2008-A188

Embedded Sensitivity as a Tool for Vibration Reduction

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Abstract

Mechanical systems can present undesirable resonance peaks in frequency ranges of interest. In order to reduce these peaks, the engineer has to change the structure, but the problem is where the changes must be introduced in the structure. Usually, the techniques for solving this problem involve the determination of sensitivity functions. However, considering experimental set-ups, the determination of sensitivity functions depends on a systematic modification of the original structure and respective response measurements, which is a costly and time consuming procedure. In these cases, the embedded sensitivity approach can be very helpful. In this work, one proposes the use of embedded sensitivity to calculate the sensitivity functions, aiming at locating deadeners in the sheet metal of a vehicle roof. After locating the deadeners in the optimum positions, it was possible to verify a strong reduction in resonance peaks of the vehicle roof, thus showing the efficiency of the procedure. The main advantage of this procedure is that it only requires FRF measurements of the vehicle in its original state, not needing any previous modification of the vehicle structure to find the sensitivity functions.

Resumen

Sistemas mecánicos pueden presentar picos de resonancia indeseables en rangos de frecuencia de interés. Con el fin de reducir estos picos, el ingeniero tiene que cambiar la estructura, pero el problema es dónde los cambios deben introducirse en la estructura. Por lo general, las técnicas para resolver este problema implica la determinación de funciones de sensibilidad. Sin embargo, considerando set-ups experimentales, la determinación de las funciones de sensibilidad depende de una sistemática modificación de la estructura original y respectivas mediciones de respuesta, que es una tarea costosa y que consume tiempo. En estos casos, el enfoque por la sensibilidad inherente puede ser muy útil. En este trabajo, proponese el uso de la sensibilidad inherente para calcular las funciones de sensibilidad, con el fin de localizar deadeners en la chapa del techo de un vehículo. Después de localizar los deadeners en las posiciones óptimas, es posible verificar una fuerte reducción en los picos de resonancia del techo del vehículo, lo cual demuestra la eficacia del procedimiento. La principal ventaja de este procedimiento es que sólo requiere mediciones de FRF del vehículo en su estado original, no necesitando ninguna modificación anterior de la estructura del vehículo para encontrar las funciones de sensibilidad.

1 Introduction

Mechanical systems, in general, present vibration as a consequence of the external excitations that it suffers during its operation. The vibration is usually expected and foreseen through design process of the system, and countermeasures are taken in design solution when vibration overcome admissible limits. In this case, a great variety of vibration control techniques may be employed based on the universe of the specialized literature.

Regarding the automotive industry, reports show that between 20 and 30 % of customer dissatisfaction is related to vibration/acoustic problems, which represent 15 to 30 % of warranty costs. Hence, solutions to vibration/acoustic problems are thoroughly studied during the design process, which inevitably lead to the following control techniques:

- isolation (reduction of transmissibility in the interface hard points);
- absorption (introduction of damping and energy dissipation);
- modal separation (avoidance of natural frequencies in the excitation frequency range);
- active control (vibration/acoustic wave cancellation).

The decision on whether technique shall be chosen depends on the cost-benefit, package availability, assembling viability, and final weight.

Aiming at reducing weight and cost in passive control techniques, one can adopt smart materials (Manz and Breitbach, 2001). These materials are piezoceramic foils and fibres that can easily be fitted to thin-walled structures like a roof panel or a dash board. Shunt circuits allow these materials to behave as an energy dissipater, thus introducing damping in the neighbouring area. Another work related to vibroacoustic performance and cost/weight reduction can be found in Carfagni et al. (2004). Using a genetic algorithm procedure, the authors find optimum locations for damping materials and stiffening ribs in vehicle sheet metal, thus achieving efficient design solutions, particularly on vibration reduction effectiveness.

In order to investigate sound level reduction in vehicle cavity, and other control opportunities, Kang et al. (2000) develop a theoretical model considering the coupling effects of the trim and air gap on the frequency response characteristics of the passenger compartment. A parametric study is performed correlating the acoustic response and the design variables, and results show that sound level is significantly reduced if the acoustic mode is related to a nodal surface parallel to the trim.

Despite the complex studies on the field that can be found in literature, vibration reduction of the resonance peaks in sheet metal are usually achieved in industry by applying deadeners. The problem is where these deadeners shall be fixed, which is usually done in a trial-and-error basis. In this context, one can rely on the embedded sensitivity method as a tool in the procedure of deadener positioning, and consequently in vibration reduction. The embedded sensitivity method is based on calculating sensitivity functions of the system that only depend on FRFs (Frequency Response Functions) of the system in pristine condition (Yang et al., 2003; Yang et al., 2004). Hence, based on the sensitivity functions, one can determine the positions of the deadeners that have most influence on the resonance peaks of the system. As a result, the best positions for the deadeners are found without needing any change in the original system for calculating the sensitivity functions. This method can also be used for characterizing structural damage and fault detection (Johnson et al., 2005).

In this work, one proposes the use of the embedded sensitivity method as a tool to find the optimum positions of the deadeners in the sheet metal of the vehicle, more specifically in the vehicle roof. The main advantage of this procedure is that it only requires FRF measurements of the vehicle in its original state, not needing any previous modification of the vehicle structure to find the sensitivity functions.

2 The Embedded Sensitivity Method

The embedded sensitivity functions are obtained from FRFs of the system, which are usually measured or computed in vibration problem diagnostics. Hence, the method is based on the hypothesis that the system can be modelled as a lumped parameter system, and one can define driving points for measuring the FRFs.

Consider the two degree-of-freedom system shown in figure 1, whose harmonic response $\mathbf{x}(\omega)$ to harmonic excitation $\mathbf{f}(\omega)$ is given by:

$$\mathbf{x}(\omega) = \left(-\omega^2\mathbf{M} + i\,\omega\mathbf{C} + \mathbf{K}\right)^{-1}\mathbf{f}(\omega) = \mathbf{H}(\omega)\,\mathbf{f}(\omega) \tag{1}$$

where $\mathbf{M}$, $\mathbf{C}$, and $\mathbf{K}$ are the inertia, damping, and stiffness matrices, respectively.

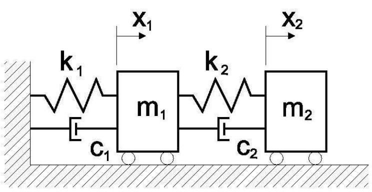


Figure 1: Analytical model of a two degree-of-freedom mechanical system.

In this case, matrix $\mathbf{H}(\omega)$ is given by:

$$\mathbf{H}(\omega) = \begin{bmatrix} H_{11}(\omega) & H_{12}(\omega) \\ H_{21}(\omega) & H_{22}(\omega) \end{bmatrix} \tag{2}$$

where:

$$H_{11}(\omega) = \frac{1}{\Delta(\omega)}\left(-\omega^2 m_2 + i\,\omega c_2 + k_2\right) \tag{3}$$

$$H_{12}(\omega) = H_{21}(\omega) = \frac{1}{\Delta(\omega)}\left(-i\,\omega c_2 - k_2\right) \tag{4}$$

$$H_{22}(\omega) = \frac{1}{\Delta(\omega)}\left[-\omega^2 m_1 + i\,\omega(c_1 + c_2) + k_1 + k_2\right] \tag{5}$$

$$\Delta(\omega) = \left[-\omega^2 m_1 + i\,\omega(c_1 + c_2) + k_1 + k_2\right]\left(-\omega^2 m_2 + i\,\omega c_2 + k_2\right) - \left(i\,\omega c_2 + k_2\right)^2 \tag{6}$$

Deriving the sensitivity functions of the system response to parameter k_1, for example, one has:

$$\frac{\partial H_{11}(\omega)}{\partial k_1} = \frac{-\left(-\omega^2 m_2 + i\,\omega c_2 + k_2\right)^2}{\Delta^2(\omega)} = -H_{11}^2(\omega) \tag{7}$$

$$\frac{\partial H_{12}(\omega)}{\partial k_1} = \frac{-\left(-\omega^2 m_2 + i\,\omega c_2 + k_2\right)\left(-i\,\omega c_2 - k_2\right)}{\Delta^2(\omega)} = -H_{11}(\omega)H_{12}(\omega) \tag{8}$$

$$\frac{\partial H_{22}(\omega)}{\partial k_1} = \frac{-\left(-i\,\omega c_2 - k_2\right)^2}{\Delta^2(\omega)} = -H_{12}^2(\omega) \tag{9}$$

As one can see in equations (7) to (9), the sensitivity functions of the system response (FRFs) to one of the system parameters (in this case, stiffness k_1) only depends on the FRFs themselves. Thus, by knowing the FRFs one can estimate the sensitivity functions of the system, with no need of knowing the system parameters (mass, damping, and stiffness). The idea can be extrapolated to the remaining parameters of the system (m_1, m_2, c_1, c_2, and k_2) without lacking generality.

Considering these results, Yang et al. (2004) proposed a more general expression for the sensitivity functions, applicable to N degree-of-freedom systems, as follows:

$$\frac{\partial H_{jk}(\omega)}{\partial k_{mn}} = -\left[H_{jm}(\omega) - H_{jn}(\omega)\right]\left[H_{km}(\omega) - H_{kn}(\omega)\right] \tag{10}$$

$$\frac{\partial H_{jk}(\omega)}{\partial c_{mn}} = i\,\omega \frac{\partial H_{jk}(\omega)}{\partial k_{mn}} \tag{11}$$

$$\frac{\partial H_{jk}(\omega)}{\partial m_m} = (i\,\omega)^2 \frac{\partial H_{jk}(\omega)}{\partial k_{m0}} \tag{12}$$

where $H_{j0} \equiv 0$ by definition.

Equations (10) to (12) refer to the embedded sensitivity functions. These functions can be used as a tool for defining the regions of the structure that shall be changed, aiming at reducing resonance peaks in the system frequency response. One can summarize the procedure in the following steps:

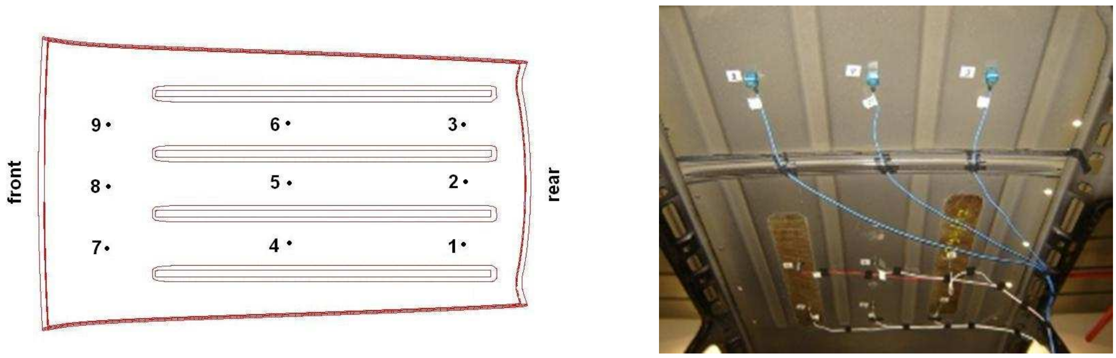
1. discretize the system and create a mesh of measuring points;
2. measure the FRFs between all discrete points of the mesh;
3. plot the FRFs and define those whose resonance peaks are excessively high in the frequency range of interest;
4. calculate the sensitivity functions for the chosen FRFs according to equations (10), (11), or (12), depending on the parameter of interest (stiffness, damping, or mass);
5. plot the sensitivity functions and determine the parameters that have more influence in the FRFs in study;
6. change the parameters in the system and redo the measurements of FRFs for comparison.

In step 5 of this procedure, all parameters that have maximum influence on the FRFs of interest are identified. This information can be used to change the system and remove/reduce undesirable resonance peaks of the system, representing a more accurate guess in the design process.

3 Positioning of Deadeners in Vehicle Roof

The NVH performance of passenger vehicles strongly depends on the fluid-structure interaction between the air in the vehicle cavity and the sheet metal structure of the vehicle. Most of noise and vibration problems related to this interaction come from resonance peaks of the sheet metal, which are excited by external forces (road, engine, wind). A reduction of these resonance peaks can be achieved by applying deadeners in the sheet metal. The problem is where these deadeners shall be fixed, which is usually done in a trial-and-error basis.

The procedure described above is applied to the problem of finding the optimum position of deadeners in the roof of a light passenger vehicle to reduce resonance peaks in the FRFs. Initially, a mesh of nine measuring points is defined over the sheet metal area of the roof (figure 2a). In order to measure the FRFs, uniaxial accelerometers are installed at these points, as shown in figure 2b. Excitation is done by an instrumented impact hammer, and the accelerometer signals are acquired by a LMS Scadas III system at a sampling frequency of 256 Hz and period of 4 s. For each excitation point, ten sample periods are acquired and averaged. The whole vehicle body is supported by pneumatic benches (figure 3) in order to configure an approximately free-free boundary condition.



(a) measuring points

(b) vehicle roof with accelerometers

Figure 2: Mesh of measuring points in the vehicle roof.

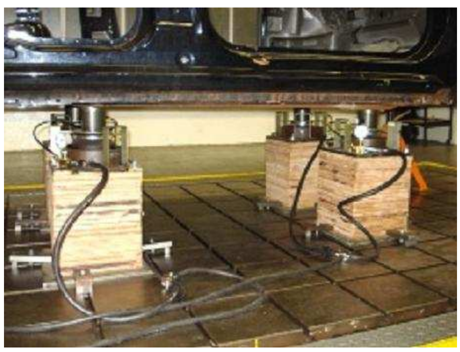


Figure 3: Vehicle body supported by pneumatic benches.

The obtained FRFs of the original system are shown in figure 4. As one can see, there is a predominant resonance peak in the frequency range of 60 to 80 Hz. Hence, the range of 60 to 80 Hz is the frequency range of interest, where the predominant resonance peak shall be reduced by fixing deadeners over the roof (increasing of roof local stiffness).

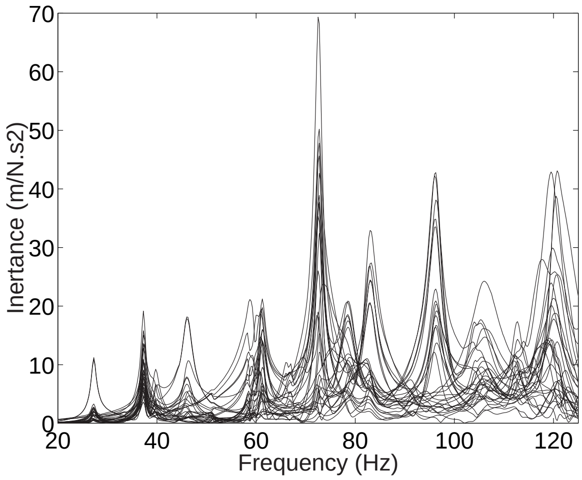


Figure 4: FRFs of the vehicle roof.

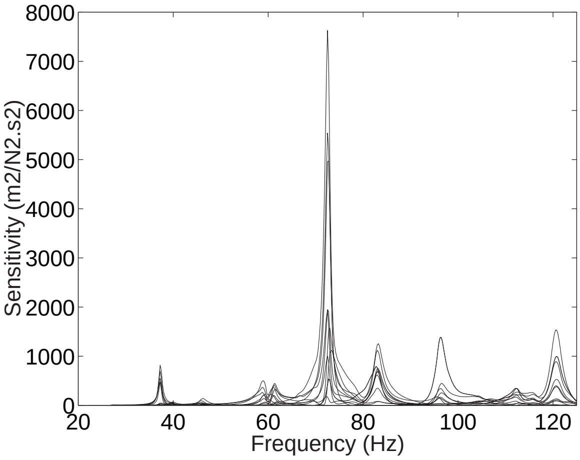
The FRFs with higher amplitude in the range of 60 to 80 Hz, in descending order, are H_{11}, H_{33}, H_{71}, H_{91}, H_{13}, H_{93}, H_{73}, H_{77}, H_{99}, and H_{79}. Hence, these are the critical FRFs in the frequency range of interest. In this work, one will focus on the four most important FRFs, which are H_{11}, H_{33}, H_{71}, and H_{91}.

The application of deadeners in sheet metals results, preponderantly, in changes of local stiffness. Hence, one can apply equation (10) to calculate the embedded sensitivity functions of the critical FRFs related to changes in local stiffness of the roof (stiffness between measuring points in the roof area). The sensitivity functions of the four most important FRFs in the frequency range of interest are presented in figure 5.

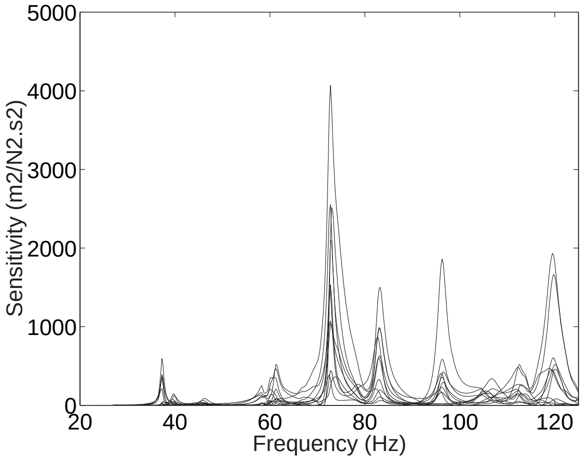
As one can see in figure 5, all FRFs have high sensitivity to certain local stiffness in the frequency range of 60 to 80 Hz. In the case of H_{11} (figure 5a), there is higher sensitivity to the stiffness between points 1-2, points 2-3, points 3-5, and points 1-4, in descending order. In the case of H_{33} (figure 5b), there is higher sensitivity to the stiffness between points 2-3, points 1-2, points 3-6, and points 1-4 (descending order). In the case of H_{71} (figure 5c), there is higher sensitivity to the stiffness between points 1-4, points 1-5, points 1-2, and points 2-3 (descending order). Finally, in the case of H_{91} (figure 5d), there is higher sensitivity to the stiffness between points 1-5, points 1-4, points 1-2, and points 3-6 (descending order). Hence, considering these results, one can visualize the areas where a change in stiffness can cause a high influence on the resonance peak of the critical FRFs in the frequency range of 60 to 80 Hz. These areas are shown in figure 6.

In this work, in order to validate the procedure, the deadeners were fixed in the areas defined in figure 6, with the exception of areas between points 1-5 and 3-5 (lined areas of figure 6), due to their lower effect on the FRFs in comparison to the other regions of the roof (figure 7). The deadeners used in the validation test are commercially available and commonly used in the production line of the vehicle. The procedure for fixing the deadeners was followed according to the supplier instructions, without any deviation. The measurement of the FRFs of the modified structure followed the same procedure described for obtaining the FRFs of the original structure.

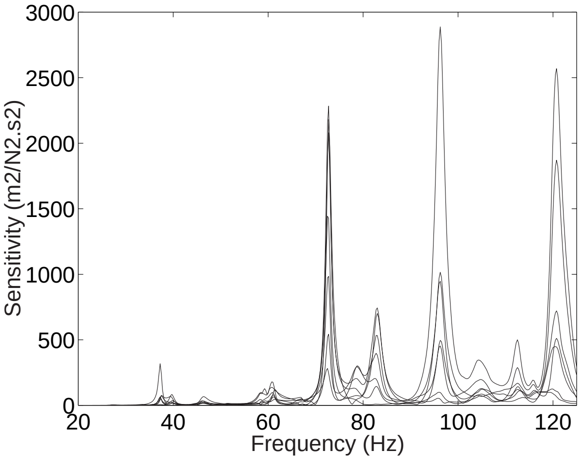
The FRFs of the modified structure, with deadeners located in the areas shown in figure 7, are presented in figure 8. As one can see, there is a significant reduction of the resonance peak in the frequency range of interest (60 to 80 Hz) when comparing the results to those obtained



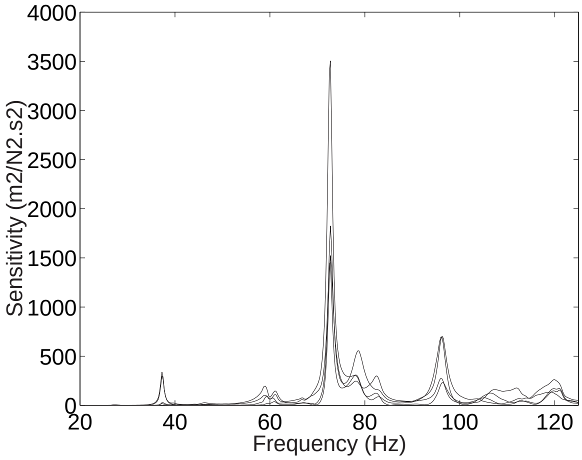
(a) $\partial H_{11}/\partial k_{mn}$



(b) $\partial H_{33}/\partial k_{mn}$



(c) $\partial H_{71}/\partial k_{mn}$



(d) $\partial H_{91}/\partial k_{mn}$

Figure 5: Embedded sensitivity functions of the four most important FRFs in the frequency range of 60 to 80 Hz.

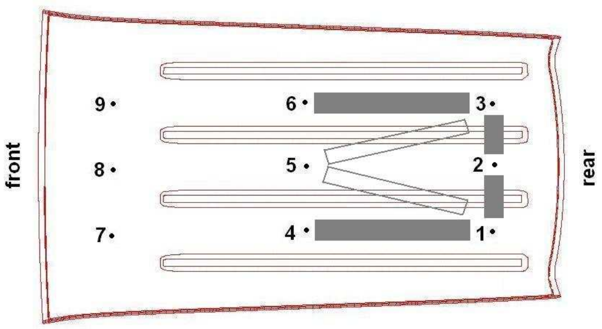


Figure 6: Areas that have higher influence on the critical FRFs in the frequency range of 60 to 80 Hz.

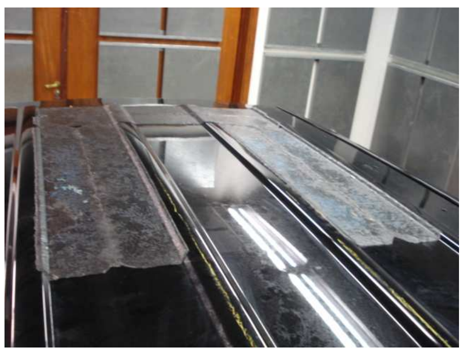


Figure 7: Deadeners fixed on the vehicle roof (modified structure).

for the pristine condition. The neighbouring peaks are also attenuated, and this can be explained by the fact that the other resonance peaks (outside the range of 60 to 80 Hz) also have some sensitivity to changes in local stiffness, as it can be seen in figures 5a to 5d. Hence, there is a side effect in adopting the proposed method, since one cannot control the effect of changes in frequencies beyond the range of interest.

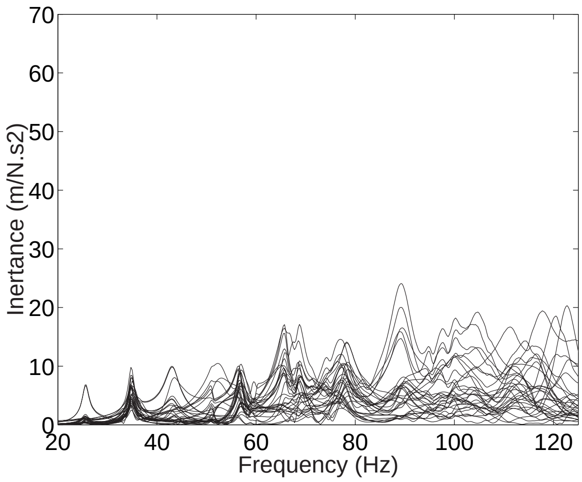


Figure 8: FRFs of the vehicle roof with deadeners at positions defined with help of the embedded sensitivity method.

Considering the obtained results, one can conclude that the method can be used to determine the location of the deadeners in the vehicle roof or, at least, be used as a first guess in the design process. The location of the deadeners was determined from experimental FRFs of the original system, without needing any change to obtain the sensitivity functions.

4 Conclusion

The embedded sensitivity method is a technique that gives the sensitivity functions of a given mechanical system based on the FRFs of the system. Hence, one can adopt the method in optimization problems, in order to find the best, or at least more suitable, design solutions for solving vibration/acoustic problems. In contrast to the commonly used and costly trial-and-error procedure, the embedded sensitivity method allows the engineer to find a more accurate guess about where changes in the structure shall be made.

In the case of study, with help of the embedded sensitivity method, deadeners were successfully located in the roof of a light passenger vehicle, resulting in significant reductions of the resonance peak in the frequency range of interest. Moreover, some additional reduction of resonance amplitude was observed in neighbouring peaks of the FRFs. The results clearly show the efficiency of the method, but also highlight side effects of the method, where one cannot control the effect of changes in frequencies beyond the range of interest.

5 Acknowledgement

The authors gratefully acknowledge Ford Motor Co. Brazil and the Laboratory of Special Tests at Tatuí Proving Ground for the support given to this project.

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