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Total Catalytic Converter Modelling for Durability Improvement

Raphaël De Matos¹, Emmanuel Foltête², Nouredine Bouhaddi², Catherine Guyard³

¹Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME)
2, Square Lafayette – BP 406 – 49004 Angers
rdematos@bavans.faurecia.com

²Institut FEMTO-ST – UMR CNRS 6174
Laboratoire de Mécanique Appliquée R. Chaléat
24 rue de l'Épitaphe – 25000 Besançon

³Faurecia Exhaust Systems
R&D Center, Bois sur Prés – 25550 Bavans

Abstract:

From the simple drain of flow to the gas cleaning, exhaust systems of automotive vehicles become complex modules playing a decisive role in the control of pollutant emissions and on acoustic comfort. In terms of depollution, the key elements are the catalysts and other systems of gas purification such as particle filters, NOx or SOx traps, etc. Catalyst is a subset in which chemical reactions are initiated with the aim of maintaining the pollutant emissions below certain rates fixed by standards.

Evolutions of emission control standards deal with service life of catalytic converters. Mechanical durability should not restrict the lifetime of catalysts. This aspect has led us to develop a prediction tool, with the aim of preselecting design solutions and reducing testing time. To reach such requirements, a total catalytic converter modeling is needed. Many efforts have been made on both numerical modelling and experimental identification. Advanced measurement techniques such as 1D pulsed ESPI have been used. A non-linear damping identification approach based on the wavelet transform of time responses has been developed and validated.

Résumé :

Afin de répondre aux exigences formulées par les normes anti-pollution, la durée de vie des supports catalytiques doit augmenter. En ce sens, un modèle complet de catalyseur d'échappement a été mis en œuvre : basé sur des moyens de mesure avancés tels que laser pulsé, ainsi que sur une méthode d'identification de l'amortissement non-linéaire cette modélisation permet la prédiction de fréquences critiques dans la plage de fonctionnement.

Mots-clefs :

Exhaust gaz purification, dynamic modeling, non-linear damping, mechanical ageing, fiability

1 Introduction

The need for strongly reducing air pollution generated by vehicles led to the elaboration of antipollution regulations. Those gave rise to well-known exhaust systems components: the exhaust catalysts.

These ones generally consist of the following under-components (FIG. 1):

- a ceramic substrate, location of chemical reactions.
- a metallic box.
- an holding mat which maintains the ceramic substrate within the steel shell.

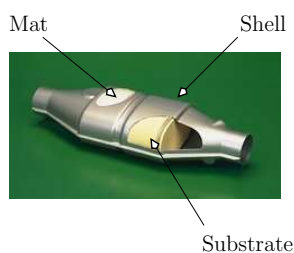


FIG. 1 – Constitutive elements of a catalytic converter

Such a device is submitted to different kind of mechanical sollicitations: on the one hand, all the vibrations generated by the engine or due to the road, as well as shocks, are transmitted to the steel shell. On the other hand, high thermal variations may reduce the service life of catalysts. As a consequence, designers must take into account all these factors to minimise their influence on durability.

Mat is a fibrous material which plays several significant roles:

- First of all it maintains the substrate, by compensating for geometrical defects and protects it from possible blows and impacts.
- Secondly, it offers a thermal insulation of the metallic shell.
- Lastly, it guarantees that the gas flow crosses the substrate in its quasi-integrity (rate higher than 99%).

For all these reasons, mats constitute essential elements of catalysts. Their ageing directly determine the service life of the catalytic function. The current state of knowledge shows that failures noted on exhaust catalysts are mainly due to the fact that the mat does not ensure its maintenance property anymore.

The experimental characterization as well as the modelling of mats are essential to improve the durability of the catalytic function. This paper does not deal with ceramic substrates as they are considered, thanks to measurements, as rigid body components.

2 Shell characterization using speckle interferometry

Electronic Speckle Pattern Interferometry (ESPI) is a recent optical technique which allows the displacement field of a harmonically vibrating structure to be measured. Based on the holographic interferometry principle, it provides a contactless, full field and instantaneous measurement by using a powerful pulsed laser and a specific CCD camera, along one two or three directions. In the past few years, a technique has been developed in order to extract quantitative data for model updating from this kind of dynamic measurements [1].

In order to perform a model updating under the best conditions as possible, the huge measured data (about one million of pixels) are reduced to the image points which correspond to the FE nodes. By using the video image, the relation between the 3D coordinates and 2D coordinates in the image, as well as the measurement direction (called sensitivity direction) are identified for each FE node.

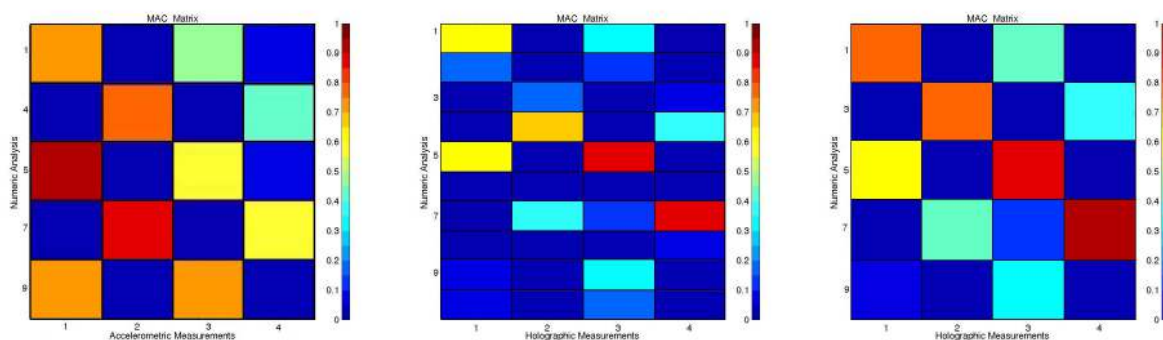
The extraction of the measured data from the displacement image is made up of two operations: the data condensation on the finite elements (FE) nodes which are visible from the observation point and the computation of the sensitivity directions. A measured value is then

2.2 Comparison between experimental and analytical results

The experimental mounting consists of an empty pipe suspended with free-free boundary conditions. The excitation force is generated by a shaker: acceleration and force are measured at the excitation point. ESPI measurements are performed under harmonic excitation at the resonant frequencies.

Because of multiple eigenvalues, accelerometric measurements do not give enough information for model updating. The MAC matrix between experimental and analytical modes shows that each experimental mode could be represented at least by two analytical modes (FIG. 3-(a)).

On the other hand, we can illustrate the improvement provided by ESPI measurements, as well as the sub-space division for multiple eigenvalues (FIG. 3-(b)(c)).



3-(a) MAC matrix considering only 16 accelerometers with sub-space division

3-(b) MAC matrix with no sub-space division

3-(c) MAC matrix with sub-space division

FIG. 3 – MAC matrix for a pipe, considering accelerometric and holographic measurements

3 Fiber mat materials characterization

As said before, mats play a decisive role in the durability of catalytic converters. Moreover, mats are not well known in dynamics, because of their structure complexity.

In the following development, we present an original method to extract modal parameters of mats [3][4].

3.1 Experimental setup

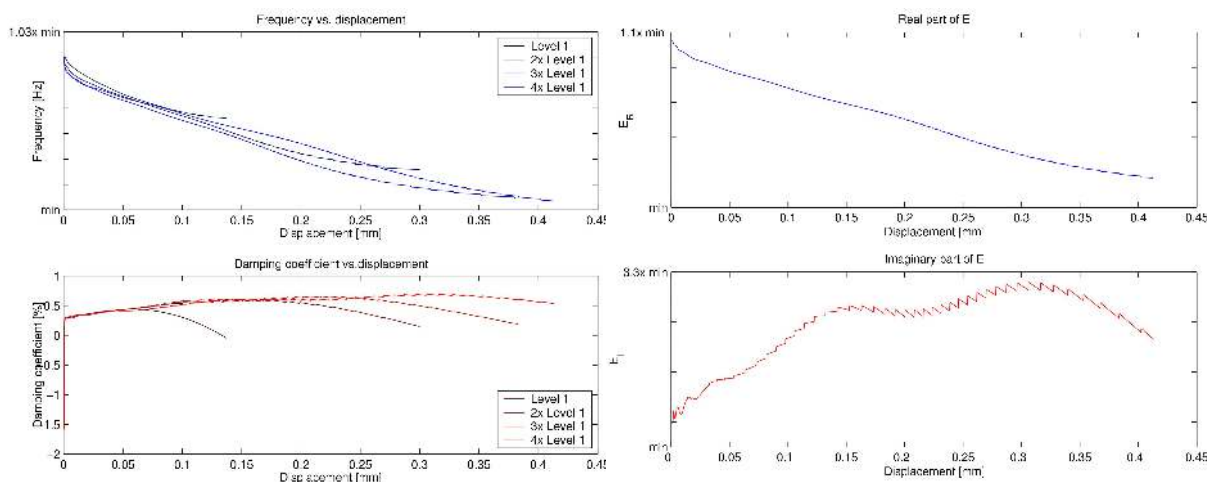
Mats are constituted of ceramic fibers. An organic binder ensures a good cohesion between these fibers in order to facilitate the manipulation. When submitted to heat, this binder flows away: on vehicle, this occurs during the first kilometers. After that and for the whole lifetime of the vehicle, mats hold on ceramic substrates without any binder.

For this reason, we have chosen to work on binder free mats, that is to say with mats that can not be manipulated safely. The experimental characterization bench has been designed in order to be able to study the dynamic response of the 1D oscillator constituted with such a material.

A thermal aged mat, considered as isotropic, is packaged in working like conditions. A harmonic force is applied to the 1D oscillator and suddenly stopped. By observing the dynamic *free* response we are able to extract a large information field by using the wavelet transform.

3.2 Data processing

Despite of the short time of measurement (due to high damping ratio), the wavelet transform gives good results as shown on FIG. 4-(a). Frequency and damping ratio are represented vs. displacement: the behavior shown is viscoelastic.



4-(a) Instantaneous Resonant frequency and Damping factor vs. displacement
4-(b) Instantaneous complex Young's modulus vs. displacement

FIG. 4 – Instantaneous Resonant frequency, damping factor and Young's modulus vs. displacement

Since the experimental bench can be assimilated to a single-degree-of-freedom system, it can be idealized to a system shown in FIG. 5-(a). Therefore, we can use the concept of viscous damping to represent the damping mechanism of viscoelastic material (FIG. 5-(b)). Mathematically, for

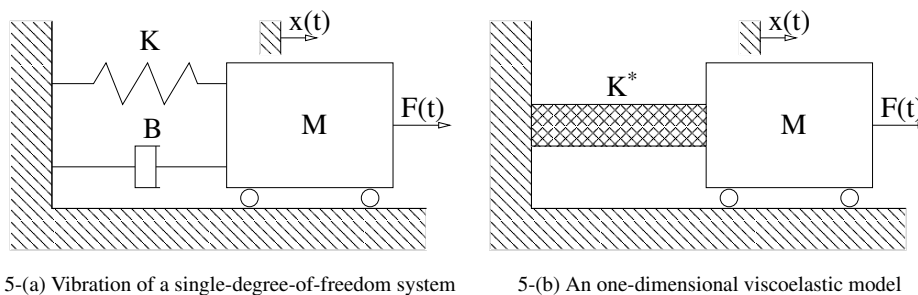


FIG. 5 – Viscous vs. viscoelastic systems

such a system the stiffness of the viscoelastic material can be modelled by the complex form, that is $K^* = K_R + jK_I$ [5]. The equations of motion of the systems shown in FIG. 5 are represented by $M\ddot{x} + B\dot{x} + Kx = 0$ for case (a), and by $M\ddot{x} + (K_R + jK_I)x = 0$ for case (b). By considering the real and imaginary parts of the above equations, it yields to:

$$K_R = M\omega_0^2 \quad K_I = 2\zeta M\omega_0^2 \quad (3)$$

where ζ is the damping factor of the system. By expressing the displacement field as a function of the geometric parameters, the Lamé coefficient μ is known. As a consequence, the complex Young's Modulus can be computed FIG. 4-(b).

4 Conclusion

ESPI is a recent measurement technology which provides a high spatial resolution. The correlation between the model and the real structure has been improved by using ESPI measurements. In addition, we have shown how to solve the problem of multiple eigenvalues: as a consequence, we would be able to perform model updating on cylindrical entities.

Concerning mats, measurements have underlined a non-linear response. The wavelet transform method allows us to extract eigen-frequency and damping ratio of mats as a function of the amplitude. Moreover, it provides a quick testing method: if classical testing method were used, we would have applied the Fourier transform technique on dozens of measurements at different amplitudes. This long and tedious step is favorably replaced by a single measurement followed by a single data processing.

The extraction of the complex stiffness is done as the characterization bench can be considered as a single-degree-of-freedom system. As a consequence, the Young modulus of the material is computed.

This will lead to a dynamic representation of a whole catalytic converter, at ambient temperature. The next step will consist in the evaluation of a wide range type of mats, at different temperatures.

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Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME)
Sophia Antipolis - 06560 Valbonne, France

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