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STOCHASTIC REDUCED-ORDER MODEL FOR DYNAMICAL STRUCTURES HAVING A MODAL DENSITY IN THE LOW FREQUENCY RANGE

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ABSTRACT

This paper is devoted to the construction of stochastic reduced-order model for dynamical structures having a high modal density in the low-frequency range. We are particularly interested in automotive vehicles which are made up of stiff parts and flexible components. This type of structure is characterized by the fact that it exhibits, in the low-frequency range, not only the classical global elastic modes but also numerous local elastic modes which cannot easily be separated from the global elastic modes. To solve this difficult problem, a new approach has recently been proposed for constructing a reduced-order computational dynamical model adapted to the low-frequency range. The proposed method requires to decompose the domain of the structure into subdomains. Such a decomposition is carried out using the Fast Marching Method. An adapted generalized eigenvalue problem is constructed using such a decomposition and allows an adapted vector basis to be computed. This basis is then used to construct the reduced-order model. Model uncertainties induced by modeling errors in the computational model are taken into account using the nonparametric probabilistic approach which is implemented in the reduced-order model. The methodology is applied on a complex computational model of an automotive vehicle.

1 INTRODUCTION

This work is performed in the context of the dynamic analysis of automotive vehicles. An automotive vehicle is made up of stiff parts and flexible components. In the low-frequency range, this type of structure is characterized by the fact that it exhibits, not only the classical global elastic modes, but also numerous local elastic modes in the same low-frequency band. With such a complex heterogeneous structure, the global elastic modes cannot clearly be separated from the local elastic modes because there are many small contributions of the local deformations in the deformations of the global elastic modes and conversely. We then have to construct a new vector basis which allows a reduced-order dynamical system to be constructed in the low frequency domain for predicting the global displacements. The vector basis of the local displacements is not orthogonal to the global displacement vector basis. Consequently, a part of the mechanical energy is transferred from the reduced-order system constructed with

the global displacements vector basis to the dynamical subsystem constructed with the local displacements vector basis and which stores a part of the mechanical energy and then, which induces an apparent damping for the reduced-order dynamical system. In order to construct a reduced-order model for the low-frequency band, which allows a good approximation of the global displacements to be predicted and then, if needed, to take into account the effects of the local displacements in the total response, a new approach [1] has recently been proposed. This method allows a basis of the global displacements and a basis of the local displacements to be calculated by solving two separated eigenvalue problems, but which requires to decompose the computational model in subdomains whose sizes are controlled. In this paper, we propose to use the Fast Marching Method for the construction of such subdomains. We construct a reduced-order model using only the basis of global displacements. In addition, in order to take into account model uncertainties induced by modeling errors in the computational model, we introduce a stochastic reduced-order model in order to taking into account the irreducible errors introduced by neglecting the local displacements. In a first part, we present the construction of the stochastic reduced-order model. Then, we present the Fast Marching Method (see [2]). Finally, we apply the methodology for a complex finite element model of an automotive vehicle.

2 DESCRIPTION OF THE METHOD

In this section, we summarize the method introduced in [1]. This method allows a basis of the global displacements and a basis of the local displacements to be constructed by solving two separated eigenvalue problems. It should be noted that these two bases are not made up of the usual elastic modes. The method is based on the construction of a projection operator which reduces the kinetic energy while the elastic energy remain exact. This method is applied to the structural part of the vibroacoustic system we are interested in.

2.1 Reference reduced model

We are interested in predicting the frequency response functions of a vibroacoustic damped structure occupying a domain Ω , in the frequency band of analysis $\mathcal{B} = [\omega_{\min}, \omega_{\max}]$ with $0 < \omega_{\min}$. Let $\mathbb{U}(\omega)$ be the complex vector of the m DOF of the structural part of the vibroacoustic computational model constructed by the finite element method. Let $[\mathbb{M}]$ and $[\mathbb{K}]$ be the mass and stiffness matrices which are positive-definite symmetric ($m \times m$) real matrices. The eigenfrequencies λ and the elastic modes $\boldsymbol{\varphi}$ in \mathbb{R}^m of the conservative part of the dynamical computational model of the structure are the solution of the following eigenvalue problem,

$$[\mathbb{K}] \boldsymbol{\varphi} = \lambda [\mathbb{M}] \boldsymbol{\varphi}. \quad (1)$$

Then an approximation $\mathbb{U}_n(\omega)$ at order n of $\mathbb{U}(\omega)$ can be written as

$$\mathbb{U}_n(\omega) = \sum_{\alpha=1}^n q_{\alpha}(\omega) \boldsymbol{\varphi}_{\alpha} = [\Phi] \mathbf{q}(\omega), \quad (2)$$

in which $\mathbf{q}(\omega) = (q_1(\omega), \dots, q_n(\omega))$ is the complex vector of the n generalized coordinates and where $[\Phi] = [\boldsymbol{\varphi}_1 \dots \boldsymbol{\varphi}_n]$ is the ($m \times n$) real matrix of the elastic modes associated with the n first eigenvalues.

2.2 Decomposition in subdomains for kinematic energy reduction.

In this section, we introduce a decomposition of the domain of the structure which allows the kinematic energy to be reduced. We then obtained an associated mass matrix which is adapted to the calculation of the global elastic modes in the low-frequency band of analysis in which there are also a large there are a large number of local elastic modes. The details of the methodology for the the continuous and the discrete cases are presented in [1].

2.2.1 Decomposition of domain Ω

Domain Ω is partitioned into n_J subdomains Ω_j such that, for j and k in $\{1, \dots, n_J\}$,

$$\Omega = \bigcup_{j=1}^{n_J} \Omega_j \quad , \quad \Omega_j \cap \Omega_k = \emptyset . \quad (3)$$

The choice of the length of subdomains is related to the smallest "wavelength" of the global elastic modes that we want to extract in presence of numerous local modes. The construction of the subdomains are presented in Section 3.

2.2.2 Projection operator

Let $\mathbf{u} \mapsto h^r(\mathbf{u})$ be the linear operator defined by

$$\{h^r(\mathbf{u})\}(\mathbf{x}) = \sum_{j=1}^{n_J} \mathbb{I}_{\Omega_j}(\mathbf{x}) \frac{1}{m_j} \int_{\Omega_j} \rho(\mathbf{x}) \mathbf{u}(\mathbf{x}) d\mathbf{x} , \quad (4)$$

in which $\mathbf{x} \mapsto \mathbb{I}_{\Omega_j}(\mathbf{x}) = 1$ if \mathbf{x} is in Ω_j and equal to 0 otherwise. The local mass m_j is defined, for all j in $\{1, \dots, n_J\}$, by $m_j = \int_{\Omega_j} \rho(\mathbf{x}) d\mathbf{x}$, where $\mathbf{x} \mapsto \rho(\mathbf{x})$ is the mass density. Let $\mathbf{u} \mapsto h^c(\mathbf{u})$ be the linear operator defined by

$$h^c(\mathbf{u}) = \mathbf{u} - h^r(\mathbf{u}) . \quad (5)$$

Function $h^r(\mathbf{u})$ will also be denoted by \mathbf{u}^r and function $h^c(\mathbf{u})$ by \mathbf{u}^c . We then have $\mathbf{u} = h^r(\mathbf{u}) + h^c(\mathbf{u})$ that is to say, $\mathbf{u} = \mathbf{u}^r + \mathbf{u}^c$. Let $[H^r]$ be the $(m \times m)$ matrix relative to the finite element discretization of the projection operator h^r defined by Eq. (4). Therefore, the finite element discretization \mathbb{U} of \mathbf{u} can be written as $\mathbb{U} = \mathbb{U}^r + \mathbb{U}^c$, in which

$$\mathbb{U}^r = [H^r] \mathbb{U}$$

and

$$\mathbb{U}^c = [H^c] \mathbb{U} = \mathbb{U} - \mathbb{U}^r \quad ,$$

which shows that $[H^c] = [I_m] - [H^r]$. Then, the reduced $(m \times m)$ mass matrix $[\mathbb{M}^r]$ is such that

$$[\mathbb{M}^r] = [H^r]^T [\mathbb{M}] [H^r] \quad ,$$

and the complementary $(m \times m)$ mass matrix $[\mathbb{M}^c]$ is such that

$$[\mathbb{M}^c] = [H^c]^T [\mathbb{M}] [H^c] \quad .$$

Using the properties of the projection operator defined by Eq. (4), it can be shown [1] that

$$[\mathbb{M}^c] = [\mathbb{M}] - [\mathbb{M}^r] \quad .$$

2.3 Global and local displacements bases

There are two methods to calculate the global displacements basis and the local displacements basis. The first one is the direct method that will be used to reduce the matrix equation. In such a method, the basis of the global displacements and the basis of the local displacements are directly calculated using matrix $[\mathbb{M}^r]$. The second one, is the double projection. This method is less intrusive with respect to the commercial software and less time-consuming than

the direct method. The global displacements eigenvectors ϕ^g in \mathbb{R}^m are solution of the following generalized eigenvalue problem

$$[\mathbb{K}]\phi^g = \lambda^g[\mathbb{M}^r]\phi^g. \quad (6)$$

The local displacements eigenvectors ϕ^ℓ in \mathbb{R}^m are solution of the generalized eigenvalue problem

$$[\mathbb{K}]\phi^\ell = \lambda^\ell[\mathbb{M}^c]\phi^\ell. \quad (7)$$

The solutions of the generalized eigenvalue problems defined by Eqs. (6) and (7) are then written, for n sufficiently large, as

$$\phi^g = [\Phi]\tilde{\phi}^g, \quad \phi^\ell = [\Phi]\tilde{\phi}^\ell, \quad (8)$$

in which $[\Phi]$, defined in Eq. (2), is the matrix of the elastic modes. The global displacements eigenvectors are the solutions of the generalized eigenvalue problem

$$[\tilde{K}]\tilde{\phi}^g = \lambda^g[\tilde{M}^r]\tilde{\phi}^g, \quad (9)$$

in which $[\tilde{M}^r] = [\Phi^r]^T[\mathbb{M}][\Phi^r]$ and $[\tilde{K}] = [\Phi]^T[\mathbb{K}][\Phi]$, and where the $(m \times n)$ real matrix $[\Phi^r]$ is such that $[\Phi^r] = [H^r][\Phi]$. The local displacements eigenvectors are the solutions of the generalized eigenvalue problem

$$[\tilde{K}]\tilde{\phi}^\ell = \lambda^\ell[\tilde{M}^c]\tilde{\phi}^\ell, \quad (10)$$

in which $[\tilde{M}^c] = [\Phi^c]^T[\mathbb{M}][\Phi^c]$ and where the $(m \times n)$ real matrix $[\Phi^c]$ is such that $[\Phi^c] = [H^c][\Phi] = [\Phi] - [\Phi^r]$. It is proven in [1] that the family $\{\phi_1^g, \dots, \phi_{3n_J}^g, \phi_1^\ell, \dots, \phi_{m-3n_J}^\ell\}$ is a basis of \mathbb{R}^m . The mean reduced matrix model is obtained by the projection of $\mathbb{U}(\omega)$ on the family $\{\phi_1^g, \dots, \phi_{n_g}^g, \phi_1^\ell, \dots, \phi_{n_\ell}^\ell\}$ of real vectors associated with the n_g first global displacements eigenvectors such that $n_g \leq 3n_J \leq m$ and with the n_ℓ first local displacements eigenvectors such that $n_\ell \leq m$. It should be noted that, if the double projection method is used, then we must have $n_g \leq n$, $n_\ell \leq n$ and $n_t \leq n$ in which $n_t = n_g + n_\ell$. Then, the approximation $\mathbb{U}_{n_g, n_\ell}(\omega)$ of $\mathbb{U}(\omega)$ at order (n_g, n_ℓ) is written as

$$\mathbb{U}_{n_g, n_\ell}(\omega) = \sum_{\alpha=1}^{n_g} q_\alpha^g(\omega) \phi_\alpha^g + \sum_{\beta=1}^{n_\ell} q_\beta^\ell(\omega) \phi_\beta^\ell. \quad (11)$$

This decomposition is then used to construct the generalized mass, stiffness and damping matrices which can be written in a block representation as

$$[\mathbb{M}] = \begin{pmatrix} M^{gg} & M^{g\ell} \\ M^{lg} & M^{ll} \end{pmatrix}, \quad [\mathbb{D}] = \begin{pmatrix} D^{gg} & D^{g\ell} \\ D^{lg} & D^{ll} \end{pmatrix}, \quad [\mathbb{K}] = \begin{pmatrix} K^{gg} & K^{g\ell} \\ K^{lg} & K^{ll} \end{pmatrix}. \quad (12)$$

2.4 Mean reduced model

The aim of this work is to construct a reduced-order model adapted to the low-frequency range in which the synthesis of the frequency responses can be obtained using only the global displacements eigenvectors. So the new approximation $\mathbb{U}_{n_g}(\omega)$ of $\mathbb{U}(\omega)$ at order n_g is written as

$$\mathbb{U}_{n_g}(\omega) = \sum_{\alpha=1}^{n_g} q_\alpha^g(\omega) \phi_\alpha^g. \quad (13)$$

The corresponding reduced-order matrix equation is than written as

$$(-\omega^2[M^{gg}] + i\omega[D^{gg}] + [K^{gg}])\mathbf{g}^g = \mathbf{F}^g \quad . \quad (14)$$

Since a part of the mechanical energy is transferred from the global eigenvectors to the local eigenvectors and induced an apparent damping, we propose to replace the damping matrix $[D^{gg}]$ by a modified damping matrix $[D_{mod}^{gg}]$ which is calculated by minimizing the distance between the frequency responses computed with the proposed reduced-order model and the frequency responses given by the reference model.

2.5 Probabilistic model of uncertainties

A probabilistic model of uncertainties is introduced in the reduced-order computational model in order to take into account the system-parameter uncertainties and the model uncertainties induced by modeling errors in the reference model from which the reduced-order model has been deduced. We also have to take into account uncertainties induced by the irreducible errors introduced by neglecting the contribution of the local displacements in the constructed reduced-order model. To take into account all these sources of uncertainties, we use the nonparametric probabilistic approach (see [4]) which consists in replacing, in the reduced-order computational model, the deterministic generalized mass, damping and stiffness matrices by random matrices. In this work, the uncertainties are not taken into account on the modified generalized damping matrix (it has previously been proven that the random frequency responses are not sensitive to the statistical fluctuations of the damping matrix in the framework of the nonparametric probabilistic approach). Therefore the matrices $[M^{gg}]$ and $[K^{gg}]$ are replaced by the random matrices $[\mathbf{M}^{gg}]$ and $[\mathbf{K}^{gg}]$ for which the probability density functions (PDF) and the generator of independent realizations are given in [4]. The probability density functions of these two random matrices depend on two dispersion parameters ($\delta_{M^{gg}}$ and $\delta_{K^{gg}}$) which have to be identified using the random frequency response of the stochastic reference model and the maximum likelihood method. Therefore, the random frequency response of the stochastic reduced-order model ($\mathbf{U}^g(\omega; \delta_{M^{gg}}; \delta_{K^{gg}})$) is solution of the equation

$$\mathbf{U}^g(\omega; \delta_{M^{gg}}; \delta_{K^{gg}}) = \sum_{\alpha=1}^{n_g} \mathbf{Q}^\alpha(\omega; \delta_{M^{gg}}; \delta_{K^{gg}}) \phi^\alpha, \quad (15)$$

$$(-\omega^2[\mathbf{M}^{gg}(\delta_{M^{gg}})] + i\omega[D_{mod}^{gg}] + [\mathbf{K}^{gg}(\delta_{K^{gg}})])\mathbf{Q}^g(\omega; \delta_{M^{gg}}; \delta_{K^{gg}}) = \mathbf{F}^g. \quad (16)$$

3 CONSTRUCTION OF THE SUBDOMAINS

For the computational model of a complex structure such as an automotive vehicle, the decomposition of the domain is not easy to be carried out because the geometry is very complex and curved. The method we propose for this decomposition is based on the Fast Marching Methods (FMM) introduced in [2] which gives a way to propagate a front (the notion of front will be defined below) on connected parts from a starting point. In this section, the FMM is summarized and then we explain how to construct the subdomains using the FMM.

3.1 Presentation of the Fast Marching Method (FMM)

Let \mathbf{x} be the generic point in \mathbb{R}^3 belonging to the complex geometry Ω . Let \mathbf{x}_0 be a fixed point belonging to Ω . Let $U(\mathbf{x})$ be a geodesic distance adapted to the geometry, between \mathbf{x} and \mathbf{x}_0 . It should be noted that for a simple 3D volume domain, such a geodesic distance would be the Euclidean distance $\|\mathbf{x} - \mathbf{x}_0\|$ in which $\|\cdot\|$ is the Euclidean norm. The front related to \mathbf{x}_0 is

defined as the subset of all the \mathbf{x} such that $U(\mathbf{x})$ has a fixed value. The FMM [2] allows the front to be propagated from starting point \mathbf{x}_0 . We then have to calculate $U(\mathbf{x})$ verifying the following nonlinear Eikonal equation

$$\|\nabla U(\mathbf{x})\| = F(\mathbf{x}) \quad , \quad \mathbf{x} \in \Omega \quad , \quad (17)$$

with ∇ the gradient with respect to \mathbf{x} , in which $F(\mathbf{x})$ is a given arbitrary positive-valued function and for which the boundary condition is written as $U(\mathbf{x}) = 0$ on Γ_0 which is a curved line or a surface containing \mathbf{x}_0 . Introducing the finite element mesh of Ω , Eq. (17) is discretized using an *upwind* approximation (forward finite difference) for the gradient (see [2]). For the particular case of a rectangular regular finite element mesh for which the mesh size is h and for which the nodes are \mathbf{x}_{ij} , we have to find $U_{ij} = U(\mathbf{x}_{ij})$ as the solution of the following equation

$$\begin{aligned} & \{\max(U_{ij} - U_{i-1,j}, U_{ij} - U_{i+1,j}, 0)\}^2 \\ & + \{\max(U_{ij} - U_{i,j-1}, U_{ij} - U_{i,j+1}, 0)\}^2 = h^2 F_{ij}^2. \end{aligned} \quad (18)$$

Since the information in Eq. (18) propagates in a unique way, this equation allows the front to be propagated from the starting point. The use of the word *Fast* in FMM is due to the fact that the nodes associated with U_{ij} and identified by Eq. (18) belong to a small domain which is called the Narrow Band (NB).

In the FMM, the algorithm introduces three groups of nodes:

- (1) *alive* nodes for which the value of U_{ij} is fixed and does not change,
- (2) *trial* nodes for which the value of U_{ij} is given but has to be updated until they become *alive* and these nodes constitute the Narrow Band,
- (3) *far* nodes which have not been reached by the front and therefore are such that $U_{ij} = +\infty$.

The front is propagated using the following algorithm:

Initialization

- Choose a starting node \mathbf{x}_0 rewritten as $\mathbf{x}_{0,0}$, which is *alive* and set $U_{0,0} = U(\mathbf{x}_{0,0}) = 0$.
- The 4 neighboring nodes of $\mathbf{x}_{0,0}$ become *trial* nodes and the associated value of U is set to hF_{ij} .
- All the other nodes are *far* nodes with associated value of U equal to infinity.

Loop

- Search among *trial* nodes, the node \mathbf{x}_{ij} with the smallest value of U .
- Remove \mathbf{x}_{ij} from *trial* nodes and add \mathbf{x}_{ij} to *alive* nodes.
- For each neighboring node of \mathbf{x}_{ij} , there are two possible cases:
 - if the neighboring node is a *far* node, add it to the *trial* nodes and its value of U is set to $U_{ij} + hF_{ij}$.
 - if the neighboring node is a *trial* node, its value of U is updated solving Eq. (18).

The loop is repeated until all the node are *alive*. For triangular meshes, the algorithm described above is unchanged but Eq. (18) must be adapted (see [3]).

3.2 Construction of the subdomains

The subdomains $\{\Omega_j, j = 1, \dots, n_J\}$ of Ω are constructed using the FMM. This construction has two steps. The first one consists in choosing the centers of the subdomains. The second one consists in generating the subdomains using these centers as starting points.

(i) Selection of the subdomains centers

The subdomains centers are chosen on the stiff parts of the computational model and are uniformly distributed on the stiff parts.

(ii) Computation of the subdomains

To construct the subdomains $\{\Omega_j, j = 1, \dots, n_J\}$ for which the subdomains centers have previously been chosen, we simultaneously propagate a front starting from each center until all the nodes become *alive* nodes with respect to one of the front. Then, the boundaries of the subdomains correspond to the meeting lines of the fronts.

4 APPLICATION

In this section, we present an application of the methodology presented in the previous sections for a complex real automotive model.

4.1 Presentation

The application is done for a computational model (Finite Element Model) of an automotive vehicle. Such a FE model has 250 000 nodes and contains various types of finite elements such as volume finite elements, surface finite elements and beam elements. The frequency band of analysis is $\mathcal{B} =]0, 120] Hz$. The structure has 1, 462, 698 DOF.

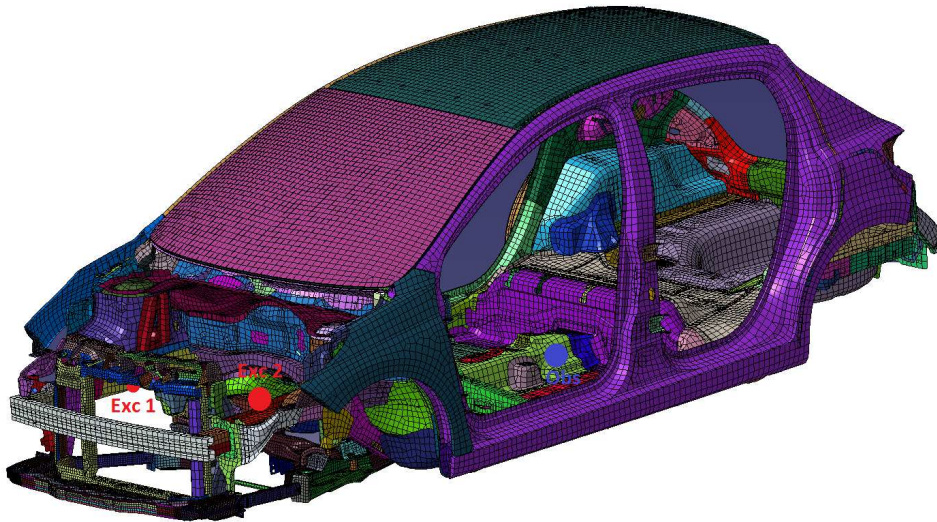


Fig. 1: The Finite Element model of an automotive vehicle

4.1.1 Decomposition of the domain

The FMM method presented in Section 3 is applied to the mesh of the structure of the automotive model. The centers of the subdomains and the subdomains obtained from these centers are represented in Fig. 2.

4.1.2 Elastic modes, global and local displacements eigenvectors

In a first step, the elastic modes are calculated with the finite element model. There are 160 eigenfrequencies in the frequency band of analysis \mathcal{B} . In a second step, the global and local

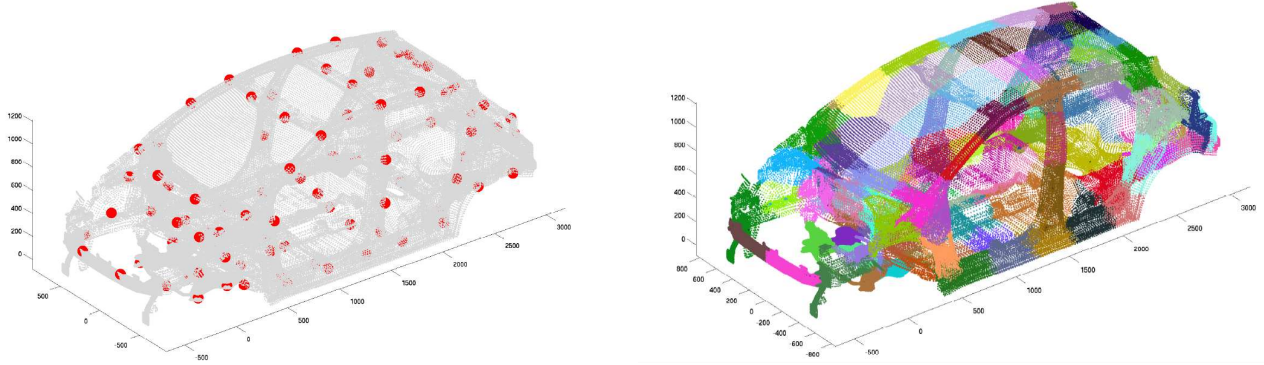


Fig. 2: Centers of the subdomains (left) and subdomains (right)

displacements eigenvectors are constructed using the double projection method. In frequency band $]0, 120]$ Hz , there are $n_g = 36$ global displacements eigenvectors and $n_\ell = 124$ local displacements eigenvectors. To see the good separation obtained between the global displacements eigenvectors and the local displacements eigenvectors, Fig. 3 displays the eleventh elastic mode (right figure) for which there are local displacements and the corresponding fourth global displacements eigenvector (left figure) for which the local displacements have been filtered.

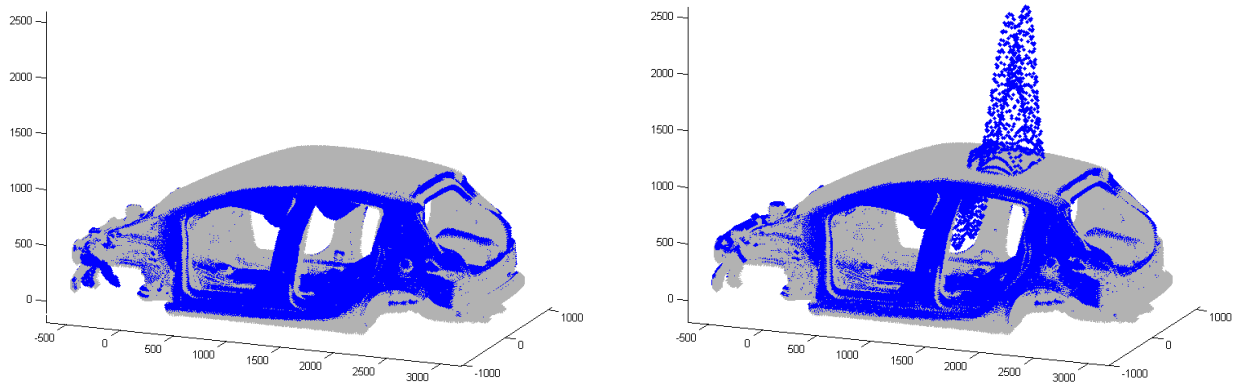


Fig. 3: Fourth global displacements eigenvector (left) and corresponding eleventh elastic mode (right).

4.2 Frequency response functions

For all $\omega \in \mathcal{B}$, the structure is subjected to an external point load equal to 1 N applied to two nodes, Exc1 and Exc2, located in the stiff part of the structure. The frequency response is calculated at one observation point, Obs₁, which is located in the stiff part (see Fig. 1). The frequency responses are calculated for different projections associated with the different bases: for the elastic modes ($n = 160$), for global displacements eigenvectors ($n_g = 36$ and $n_\ell = 0$) and finally, for global displacements eigenvectors with the modification of the damping matrix ($n_g = 36$ and $n_\ell = 0$) and for global and local displacements eigenvectors ($n_g = 36$ and $n_\ell = 124$). The modulus, in log scale, of the frequency response function is displayed in Fig. 4. It can be seen that the responses calculated using global and local displacements eigenvectors are exactly the same that the response calculated using the elastic modes. In the Fig. 4, we can see that the response calculate with the global displacement eigenvector gives a good approximation of the response calculate with the elastic modes. Moreover, the response

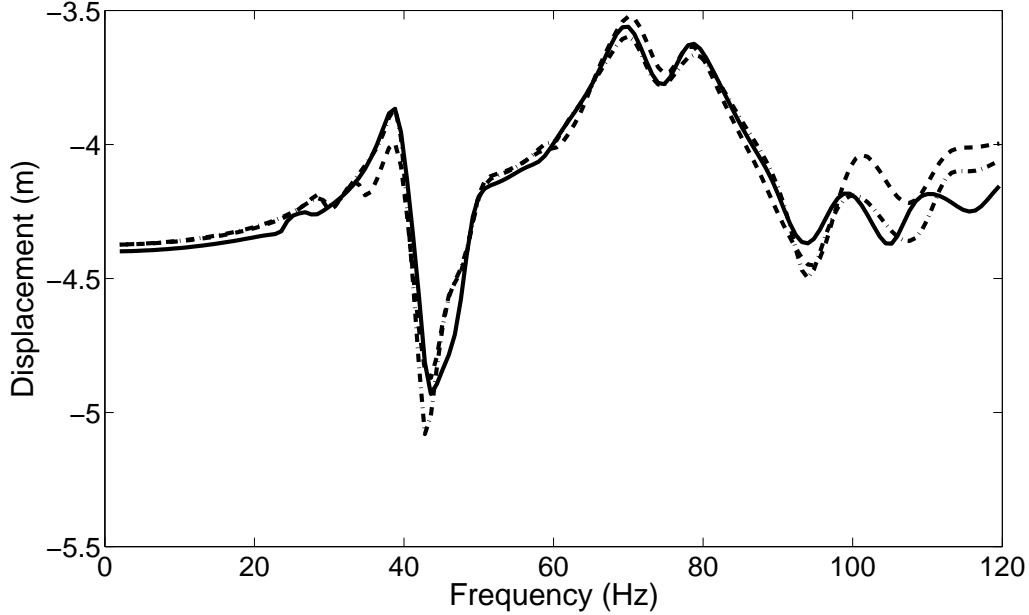


Fig. 4: Modulus, in log scale, of the frequency response function for Obs_1 . Comparisons between different projection bases: elastic modes (solid line), global displacements eigenvectors only (dashed line), global displacements eigenvectors with modification of the damping matrix (mixed line), global and local displacements eigenvectors (superimposed to the solid line).

calculated with the modified damping matrix gives a better result.

4.3 Random frequency response

In this section, we calculate the stochastic reduced model. We use 1000 simulations for the Monte Carlo simulation method. The confidence regions corresponding to a probability level $P_c = 0.95$ is plotted in Fig.5. The region of confidence of the reference model (calculate with the elastic modes) is included in the region of confidence calculate with the stochastic reduced order model.

5 CONCLUSION

In this work, we have applied a new methodology allowing a reduced-order computational dynamical model to be constructed for the low-frequency domain in which there are simultaneously global and local elastic modes which cannot easily be separated with usual methods. Moreover, we have used the Fast Marching Method which is adapted to complex geometry for constructing the subdomains and the adapted reduced-order computational model. An associated stochastic reduced-order model has then been introduced to take into account uncertainties in the adapted reduced-order model. The results obtained are good with respect to the objectives fixed in this work consisting in constructing a reduced-order model with a very low dimension, which has the capability to predict the frequency responses in the low-frequency range.

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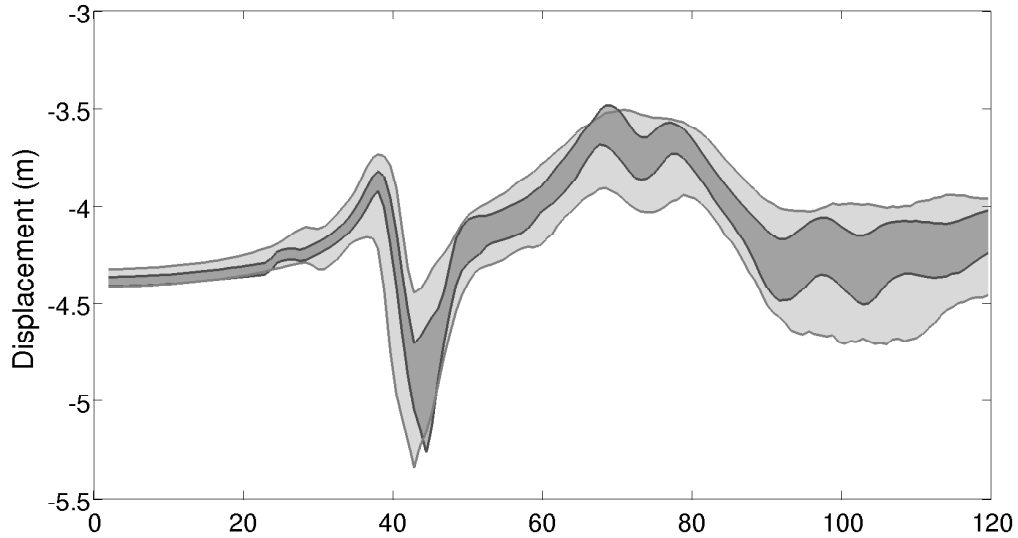


Fig. 5: Modulus, in log scale, of the random frequency response function. Confidence region (dark gray region) computed with the reference computational model. Confidence region (light gray region) computed with the stochastic reduced-order model.

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