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A robust component mode synthesis method for stochastic damped vibroacoustics

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ABSTRACT

In order to reduce vibrations or sound levels in industrial vibroacoustic problems, the low-cost and efficient way consists in introducing visco- and poro-elastic materials either on the structure or on cavity walls. Depending on the frequency range of interest, several numerical approaches can be used to estimate the behavior of the coupled problem. In the context of low frequency applications related to acoustic cavities with surrounding vibrating structures, the finite elements method (FEM) is one of the most efficient techniques. Nevertheless, industrial problems lead to large FE models which are time-consuming in updating or optimization processes. A classical way to reduce calculation time is the component mode synthesis (CMS) method, whose classical formulation is not always efficient to predict dynamical behavior of structures including visco-elastic and/or poro-elastic patches. Then, to ensure an efficient prediction, the fluid and structural bases used for the model reduction need to be updated as a result of changes in a parametric optimization procedure. For complex models, this leads to prohibitive numerical costs in the optimization phase or for management and propagation of uncertainties in the stochastic vibroacoustic problems. In this paper, the formulation of an alternative CMS method is proposed and compared to classical ($\mathbf{u}$,p) CMS method: the Ritz basis is completed with static residuals associated to visco-elastic and poro-elastic behaviors. This basis is also enriched by the static response of residual forces due to structural modifications, resulting in a so-called robust basis, also adapted to Monte Carlo simulations for uncertainties propagation using reduced models.

1. Introduction

In transports industry, reduction of vibration and acoustic levels using industrial vibroacoustic numerical models leads to large and costly problems. Solving dissipative systems in presence of uncertain parameters is still a challenge. The techniques which are classically used in the low frequency range are the finite/infinite elements or boundary elements methods [1], their frequency limits being directly related to the size of the elements compared to the wavelength and to the computer limits. When the frequency range of interest is becoming too high for these approaches, some specific methods are available, often based on wave approaches or power/energy flow analyzes [2]. In this paper we will mainly focus on a specific problem, which is the vibroacoustic analysis of damped closed systems, exhibiting an acoustic cavity surrounded

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Nomenclature

$\mathbf{u}$	structural displacement
$\mathbf{v}$	velocity on a surface
$\mathbf{n}$	normal vector of fluid domain
p	pressure
V_s	structural domain
V_f	fluid domain
S_u	surface of fluid–structure coupling
S_a	acoustic absorbing surface
∂V_s^f	structural surface on which external force is applied
$\mathbf{f}_s$	external force applied on structure
c	speed of sound in fluid
ρ_f	fluid density
Z_a	acoustic impedance
ω	angular frequency (rad/s)
f	frequency (Hz)
U	structural displacement vector, physical coordinates
$\mathbf{q}^s$	structural displacement vector, generalized coordinates
$\mathbb{U}$	random vector corresponding to U
P	pressure vector, physical coordinates
$\mathbf{q}^f$	pressure vector, generalized coordinates
$\mathbb{P}$	random vector corresponding to P
M	mass matrix
$\bar{M}$	reduced mass matrix
$\mathbb{M}$	random matrix corresponding to M
K	stiffness matrix
$\bar{K}$	reduced stiffness matrix
$\mathbb{K}$	random matrix corresponding to K
A_f	absorbing matrix
$\bar{A}_f$	reduced absorbing matrix
$\mathbb{A}$	random matrix corresponding to A_f
F_s	external force vector
C	coupling matrix
Y	physical coordinates vector
θ	random variable
G	shear modulus of viscoelastic material
T_s, T_f	reduction bases of structure and fluid domains
T	temperature
$\Re\{.\}$	real part
$E\{.\}$	first statistical moment

by a vibrating structure. For this kind of problem, the finite element method is clearly the most appropriate technique to deal with industrial geometries, even if it is limited to the low frequency range, which is the domain of interest in this work.

1.1. Vibroacoustic conservative problem

Because of the proximity of the problem topology with structural dynamics, the concept of modal analysis has been naturally extended to vibroacoustics. In the low-frequency range, this is of particular interest in the context of engineering design, since some trends can help the designer to make decisions using a fully conservative model, which is easy to implement numerically. Modeling damping terms is clearly the hardest thing during the whole process, so using conservative models avoid a difficult step, which can be acceptable only at early design stage, in particular in applications where noise and vibrations are among the design criteria. In this context, using vibroacoustic normal modes can be interesting in a engineering point of view.

In a numerical point of view, even this non-dissipative case still induces difficulties, in particular because the finite elements method (FEM) based on the classical displacement–pressure ($\mathbf{u}$,p) formulation leads to a coupled problem which is large and not symmetric [3], and the very efficient eigenvalue solvers dedicated to symmetric problems, which have been developed for years, cannot be applied. Of course, more general solvers can be used, but an alternative way is to transform the initial problem in a symmetric one, using symmetrization techniques [4,5]. These techniques can be either based only on mathematical considerations (by transforming unsymmetric matrices into symmetric ones), or on physical considerations, by choosing, instead or added to pressure p, another variable in the fluid domain. Among the available descriptions, it has been shown [3] that using the displacement potential leads to a well-posed problem in the static case. Some other formulations leading to symmetric system are for example acoustic field displacement, which is complicated by its irrotationality constraint [6]; velocity potential, whose topology is not classic [7,8] (the double sized state-space has to be used for eigenvalue problem); or combination of two variables, pressure and displacement potential for example [9,3], which doubles the number of DOFs.

1.2. Vibroacoustic damped problem

In order to practically reduce sound level, the low-cost and efficient way consists in introducing visco- and poro-elastic materials, most of the time after the initial design of the structure. The case of viscoelastic damped structure coupled with compressible fluid is considered here and the finite elements (FE) model of visco-elastic structures which is used in this paper is available in literature [10,11]. Resonances dominated by fluid cavity are controlled by poro-elastic materials. The two classical ways of using such materials in FE models is either to consider the acoustic impedance of the material (the material being modeled by a boundary condition on fluid domain) or to consider the modeling of porous media using for example the Biot–Allard theory [12–14] whose FE models need a discretization of the poro-elastic domain. For both